First Results from AGS E949 on $K^+ \to \pi^+ \nu\bar{\nu}$

David E. Jaffe, BNL

- Introduction
- The experiment
- The results
- Conclusion

What are K^+, π^+, ν and $\bar{\nu}$?

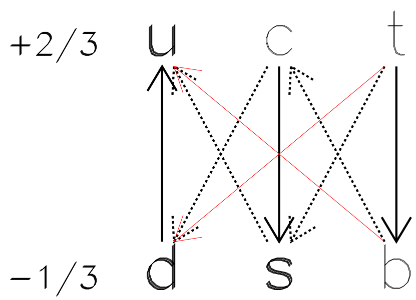
Symbol	Name	Quark content	Charge	Spin	Mass (MeV/c^2)	Lifetime (ns)
K^+	K meson or kaon	$u\bar{s}$	+1	0	493.7	12.4
π^+	pi meson or pion	$u\bar{d}$	+1	0	139.6	26.0
ν	neutrino (lepton)	-	0	1/2	≈ 0	∞
π^0	pi-zero meson	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	+0	0	135	8.4×10^{-8}
e^-	electron (lepton)	-	+1	1/2	0.511	∞
μ^+	muon (lepton)	-	+1	1/2	105.6	2197
u	up quark	-	+2/3	1/2	≈ 3	-
d	down quark	-	-1/3	1/2	≈ 7	-
s	strange quark	-	-1/3	1/2	≈ 100	-
p	proton (baryon)	uud	+1	1/2	938.3	$> 5 \times 10^{41}$
n	neutron (baryon)	udd	0	1/2	939.6	8.9×10^{11}

1 MeV = 1,000,000 eV   1 ns = 1/1,000,000 seconds

The $\bar{\nu}$ is the antiparticle of ν.

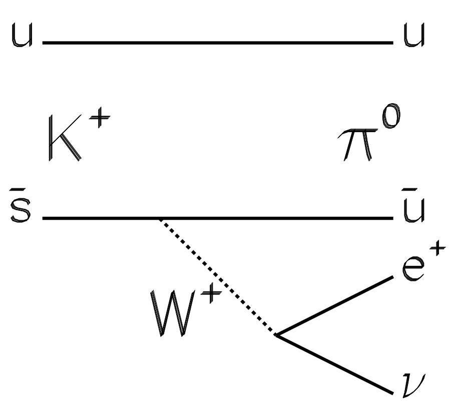
Some decay modes: $\mathcal{B}(\mathrm{K}^+ \to \pi^+\pi^0) = 21\%$, $\mathcal{B}(\mathrm{K}^+ \to \mu^+\nu) = 63\%$, $\mathcal{B}(\pi^+ \to \mu^+\nu) = 100\%$, $\mathcal{B}(\pi^0 \to \gamma\gamma) = 99\%$, $\mathcal{B}(\mu^+ \to e^+\bar{\nu}_e\nu_\mu) = 100\%$

$K^+ \to \pi^+ \nu \bar{\nu}$ probes the basic constituents of matter

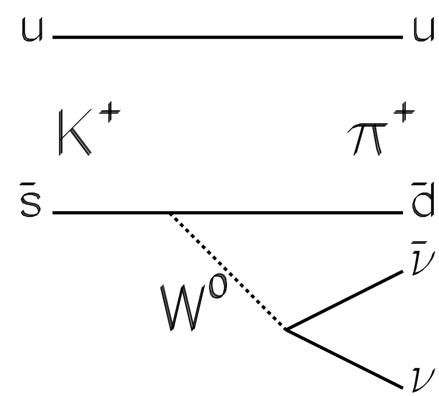


Heavy quarks decay to lighter quarks via the weak interaction

By the early 1970's...



Observed (5%)



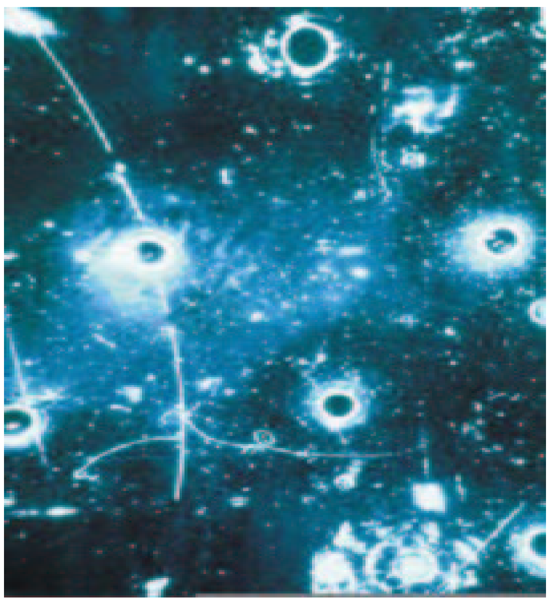
Not observed ($<10^{-6}$)

All observed flavor-changing decays also change electric charge

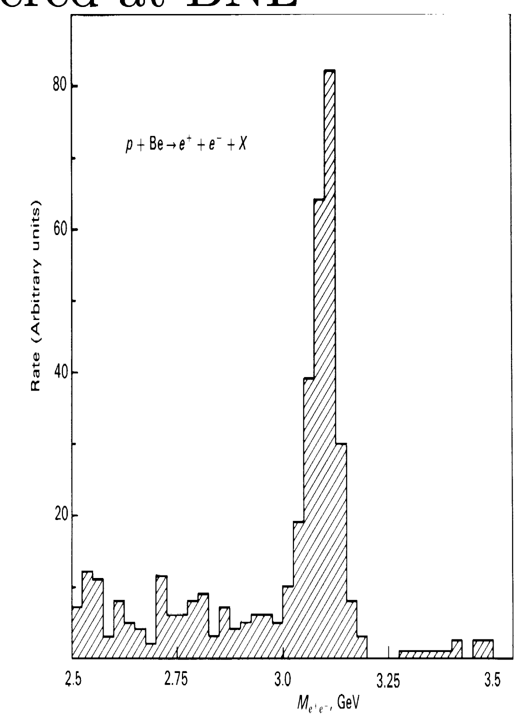
No evidence of flavor-changing neutral currents (FCNC) as predicted by theory of the time.

New theory, now known as the Standard Model (SM), predicted suppression of FCNC decays (i.e., $K^+ \to \pi^+ \nu\bar{\nu}$)with postulate of a new charge +2/3 quark (charm).

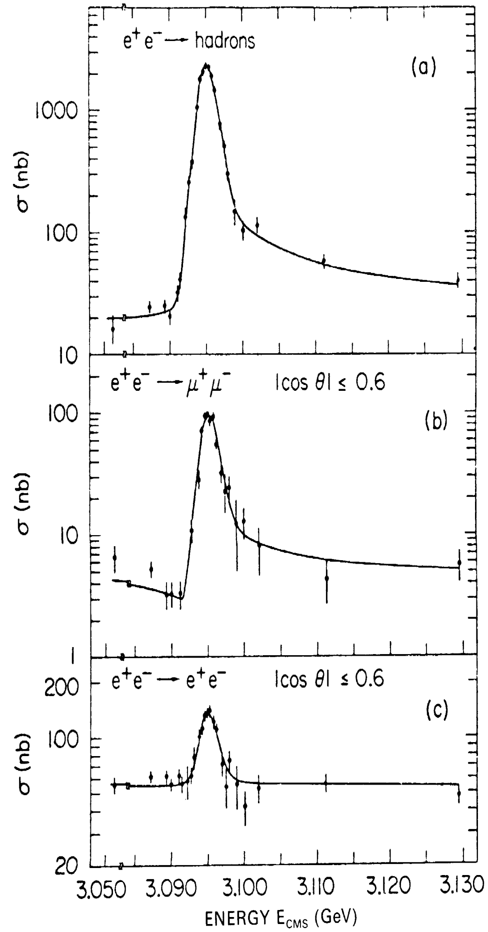
1973 NC observed in neutrino interactions at CERN



November 1974 Charm quark discovered at BNL

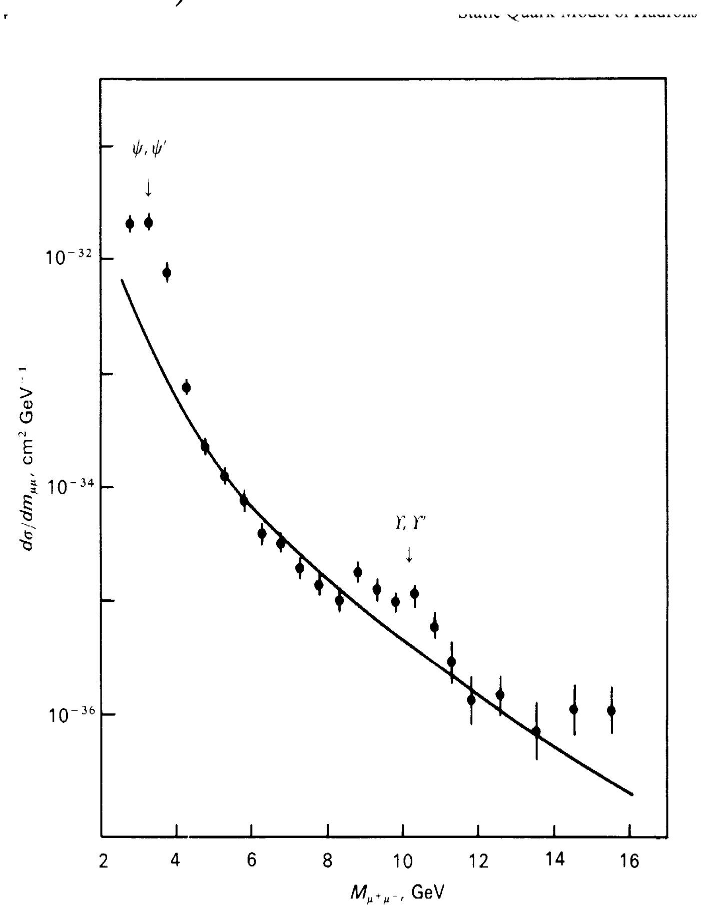


and SLAC.



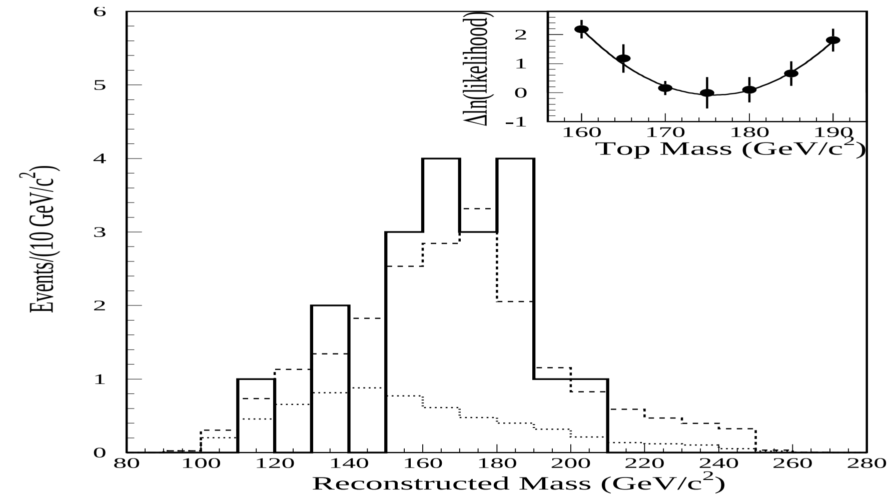
igure 5.9 Results of Augustin *et al.* (1974) showing the observation of the ψ/J resonance of ıass 3.1 GeV, produced in e^+e^- annihilation at the SPEAR storage ring, SLAC.

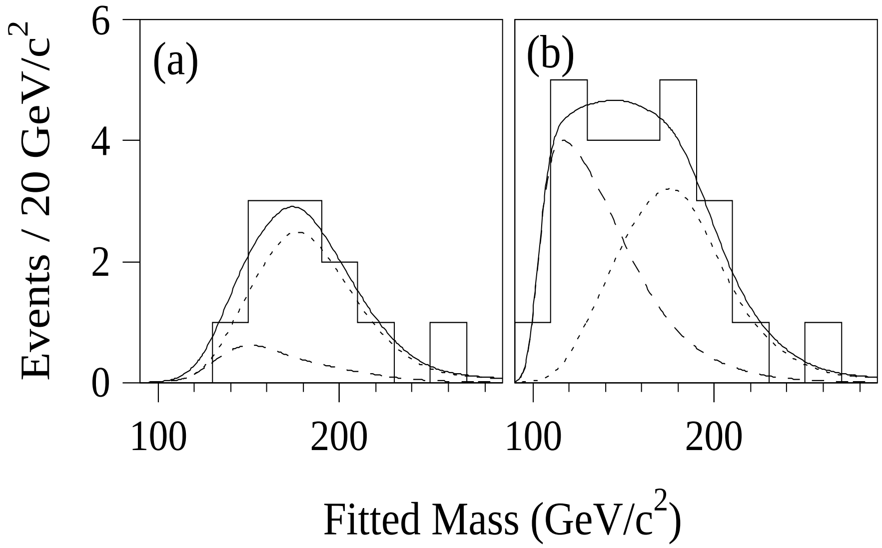
1977 Bottom quark (3rd generation) discovered at FNAL

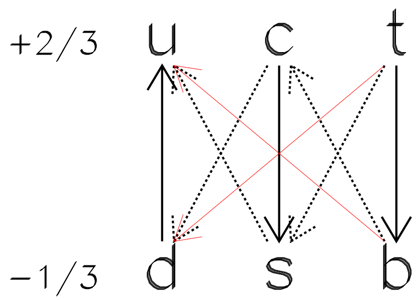


ure 5.14 First evidence for the upsilon resonances Υ, Υ', obtained by Herb *et al.* (1977) from

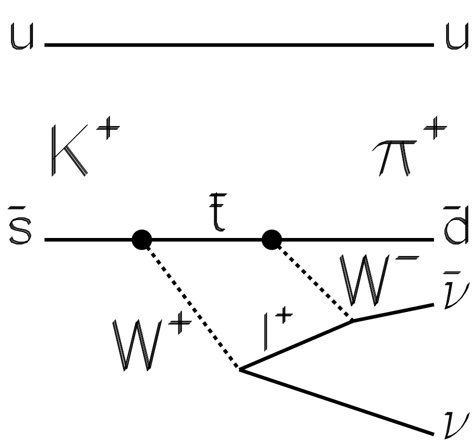
1995 Discovery of top at FNAL







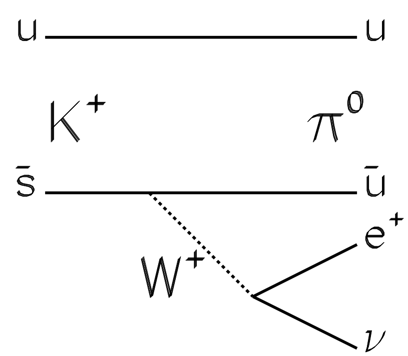
Third generation with $m_t >> m_c, m_u$ permits $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ decay at second order.



FCNC of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ in SM

$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) \propto |V_{\mathrm{ts}}^* V_{\mathrm{td}}|^2$

$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$



Strong interaction (QCD) part of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ decay is related by isospin to $K^+ \to \pi^0 e^+\nu$ decay.

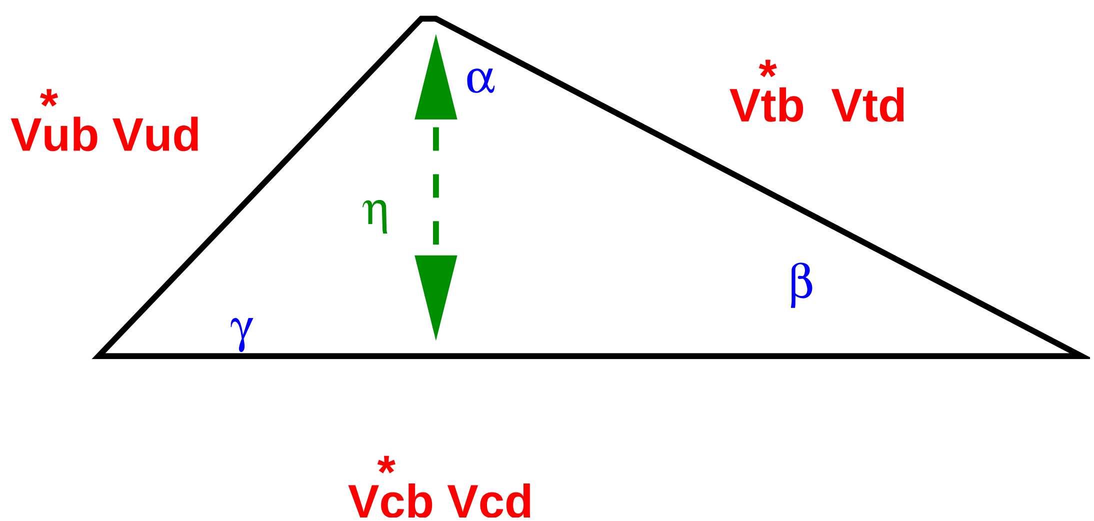
In the SM the CKM matrix relates flavor and weak eigenstates. It's a 3X3 unitary matrix:

$$\begin{pmatrix} \mathrm{V}_{\mathrm{ud}}^* & \mathrm{V}_{\mathrm{cd}}^* & \mathrm{V}_{\mathrm{td}}^* \\ \mathrm{V}_{\mathrm{us}}^* & \mathrm{V}_{\mathrm{cs}}^* & \mathrm{V}_{\mathrm{ts}}^* \\ \mathrm{V}_{\mathrm{ub}}^* & \mathrm{V}_{\mathrm{cb}}^* & \mathrm{V}_{\mathrm{tb}}^* \end{pmatrix} \begin{pmatrix} \mathrm{V}_{\mathrm{ud}} & \mathrm{V}_{\mathrm{us}} & \mathrm{V}_{\mathrm{ub}} \\ \mathrm{V}_{\mathrm{cd}} & \mathrm{V}_{\mathrm{cs}} & \mathrm{V}_{\mathrm{cb}} \\ \mathrm{V}_{\mathrm{td}} & \mathrm{V}_{\mathrm{ts}} & \mathrm{V}_{\mathrm{tb}} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

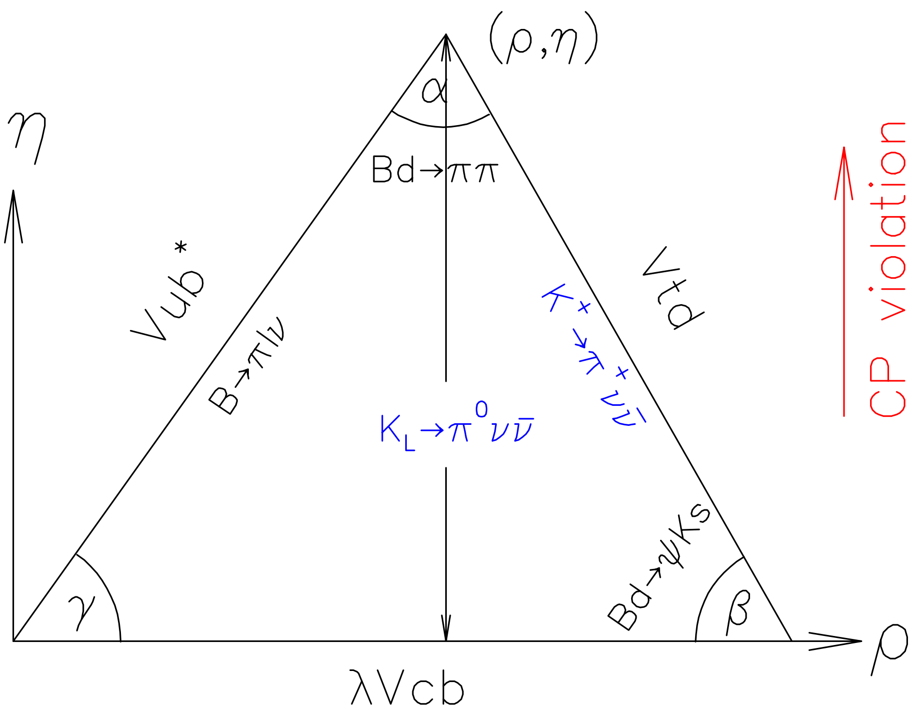
This gives 6 relations equal to 0. For example:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

can be drawn in the complex plane as a triangle (Unitarity triangle):



Reactions with small theoretical uncertainties



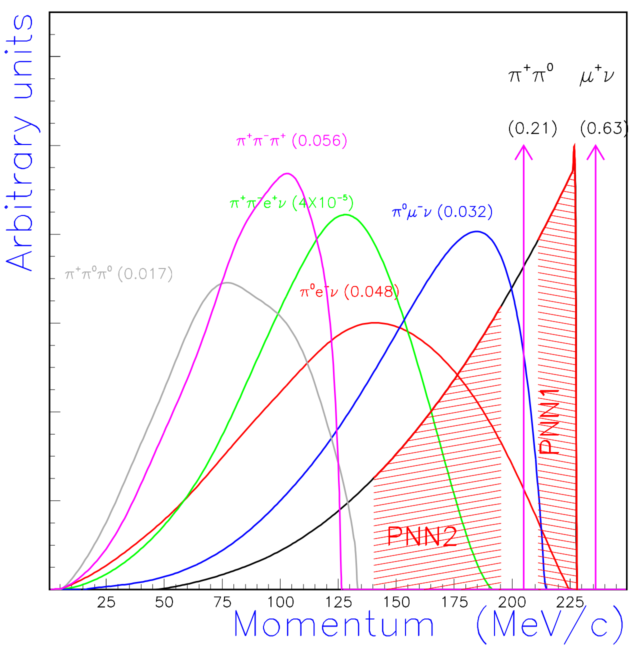
Process	Experiments
$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$	E787/E949
$\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})$	KOPIO
$\mathcal{A}(B \to J/\psi\mathrm{K}^0_\mathrm{S}; t)$	BaBar, Belle
$\Delta m_s/\Delta m_d$	CDF, D0

$\mathcal{A}(B \to J/\psi\mathrm{K}^0_\mathrm{S}; t)$ = time-dependent decay rate asymmetry; a manifestation of CP violation. $\Delta m_s/\Delta m_d$ = ratio of 'mixing' frequencies of neutral B mesons.

Comparison of $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$, $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})$ and $\sin 2\beta$ provides a clean and direct comparison of CP violation between the K and B sectors.

Experimental Considerations for $K^+ \to \pi^+ \nu\bar{\nu}$

- 3-body decay with 2 missing particles $\Rightarrow 0 \leq P(\pi^+) \leq 227\text{MeV}/c$
- Must veto to $\leq 10^{-3}$/ extra particle
- **Particle identification (PID) is essential.**



$P(\pi^+)$ **in** K^+ **rest frame**

Decay	$\mathcal{B}$	PID	veto	kine.
$\text{K}^+ \to \pi^+\pi^0$	0.21	-	$\surd\,\surd$	$\surd$
$\text{K}^+ \to \mu^+\nu$	0.63	$\surd$	-	$\surd$
$\text{K}^+ \to \mu^+\nu\gamma$	0.005	$\surd$	$\surd$	-
$\text{K}^+ \to \pi^0\mu^+\nu$	0.032	$\surd$	$\surd\,\surd$	-
$\text{K}^+ \to \pi^0 e^+\nu$	0.048	$\surd$	$\surd\,\surd$	-
$\text{K}^+ \to \pi^+\pi^-\pi^+$	0.056	-	$\surd$	$\surd\,\surd$

"kine." = kinematic suppression

$\mathcal{B}(\text{K}^+ \to \pi^+\nu\bar{\nu}) = 0.000000000077$

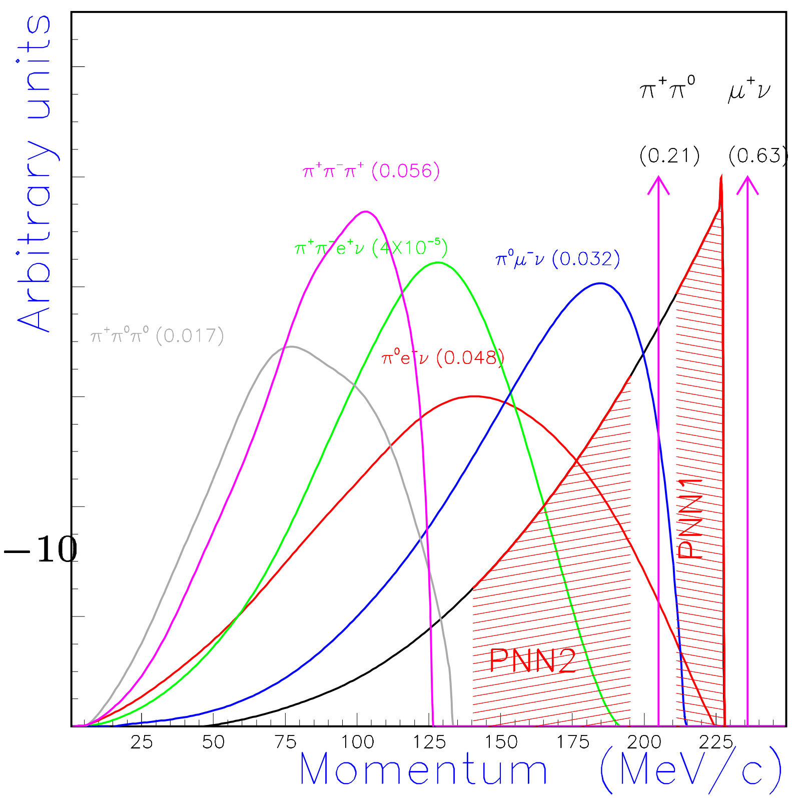
$K^+ \to \pi^+\nu\bar{\nu}$: Difficult, but not impossible!

Name	"PNN2"	"PNN1"
P_π (MeV/c)	[140,195]	[211,229]
Years	1996-97	1995-98
Stopped K^+	1.7×10^{12}	5.9×10^{12}
Candidates	1	2
Background	1.22 ± 0.24	0.15 ± 0.05
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

E787
$K^+ \to \pi^+\nu\bar{\nu}$
results

PNN1: PRL **88**, 041803 (2002).

PNN2: limit at 90%CL is combined result from 1996 (PL **B537**, 211 (2002)) and 1997 (hep-ex/0403034) data.



SM: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$

Buchalla& Buras, NP**B548** 309 (1999);

Isidori, hep-ph/0307014;Buras, hep-ph/0402112

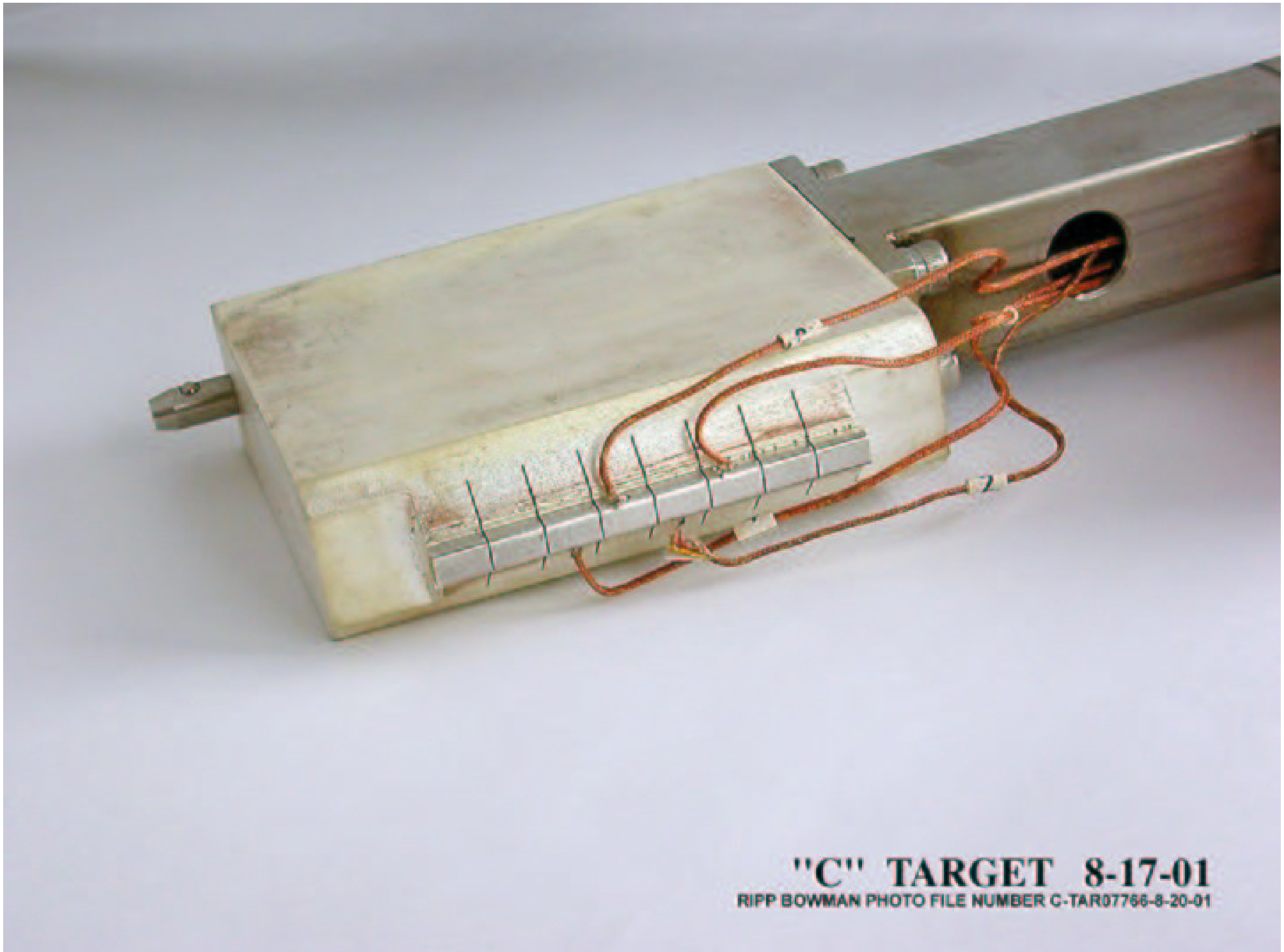
$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = 0.77 \times 10^{-10}$ means one out of $\sim 13,000,000,000$ K^+ decays to $\pi^+\nu\bar{\nu}$. So we need to make trillions (10^{12}) of K^+.

The AGS (Alternating Gradient Synchrotron) can accelerate and extract a beam of $\approx 60 \times 10^{12}$ protons at a momentum of 24 GeV/c over a ~ 2 second interval ("spill") every 5 seconds. The protons are directed onto a **platinum target** and lots of particles are produced among them π^+ and K^+.

The particles produced near 0° are directed into the Low Energy Separated Beamline (LESB III) which purifies the beam by electrostatically separating the K^+ from the π^+ and focusses them onto the E949 target.

The beam incident on the E949 target contains four K^+ for every π^+ and is the purest kaon beam in the world. Approximately 3.5×10^6 K^+ stop in the E949 target during each spill.

Platinum target before E949 data taking



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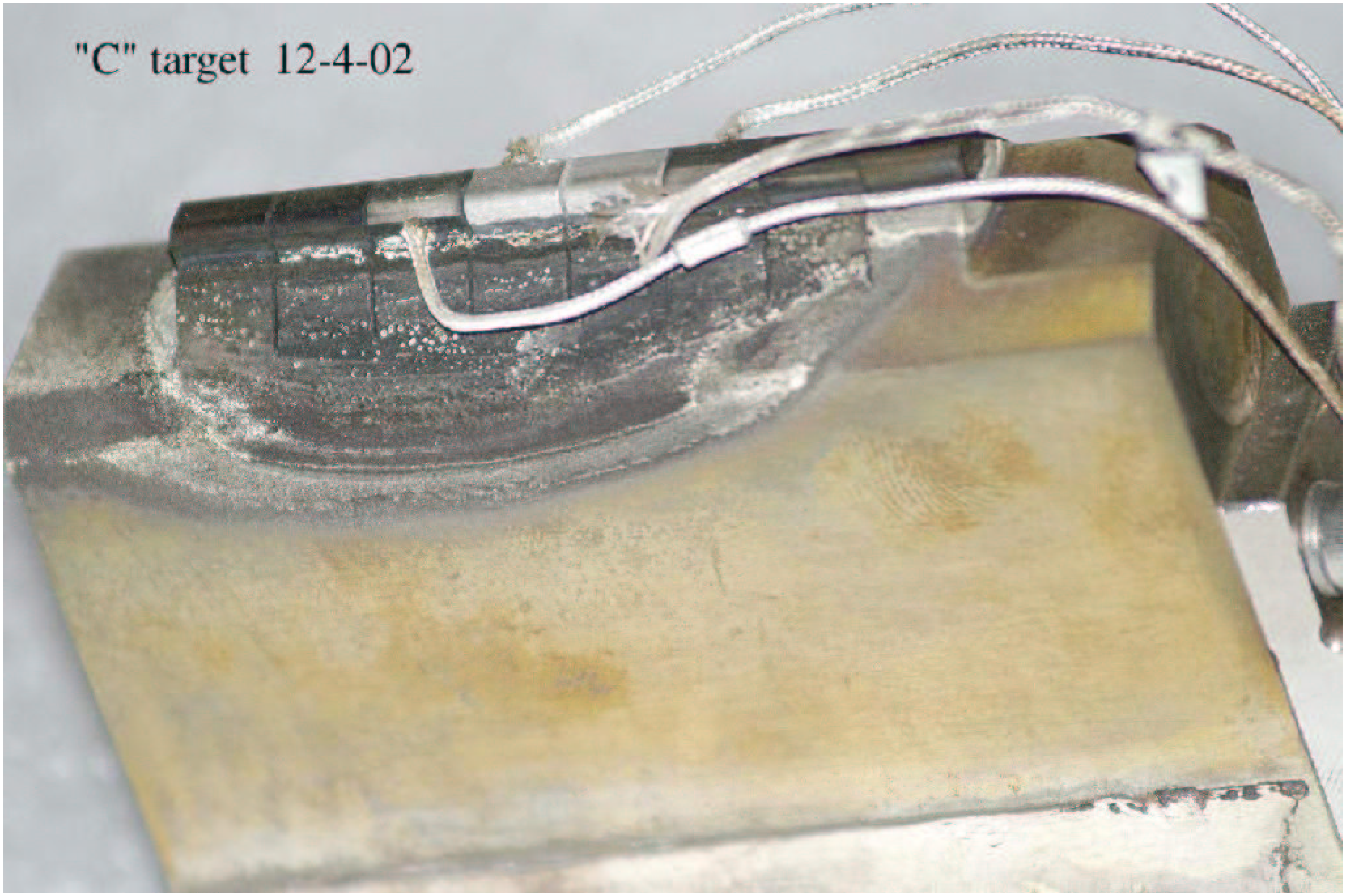

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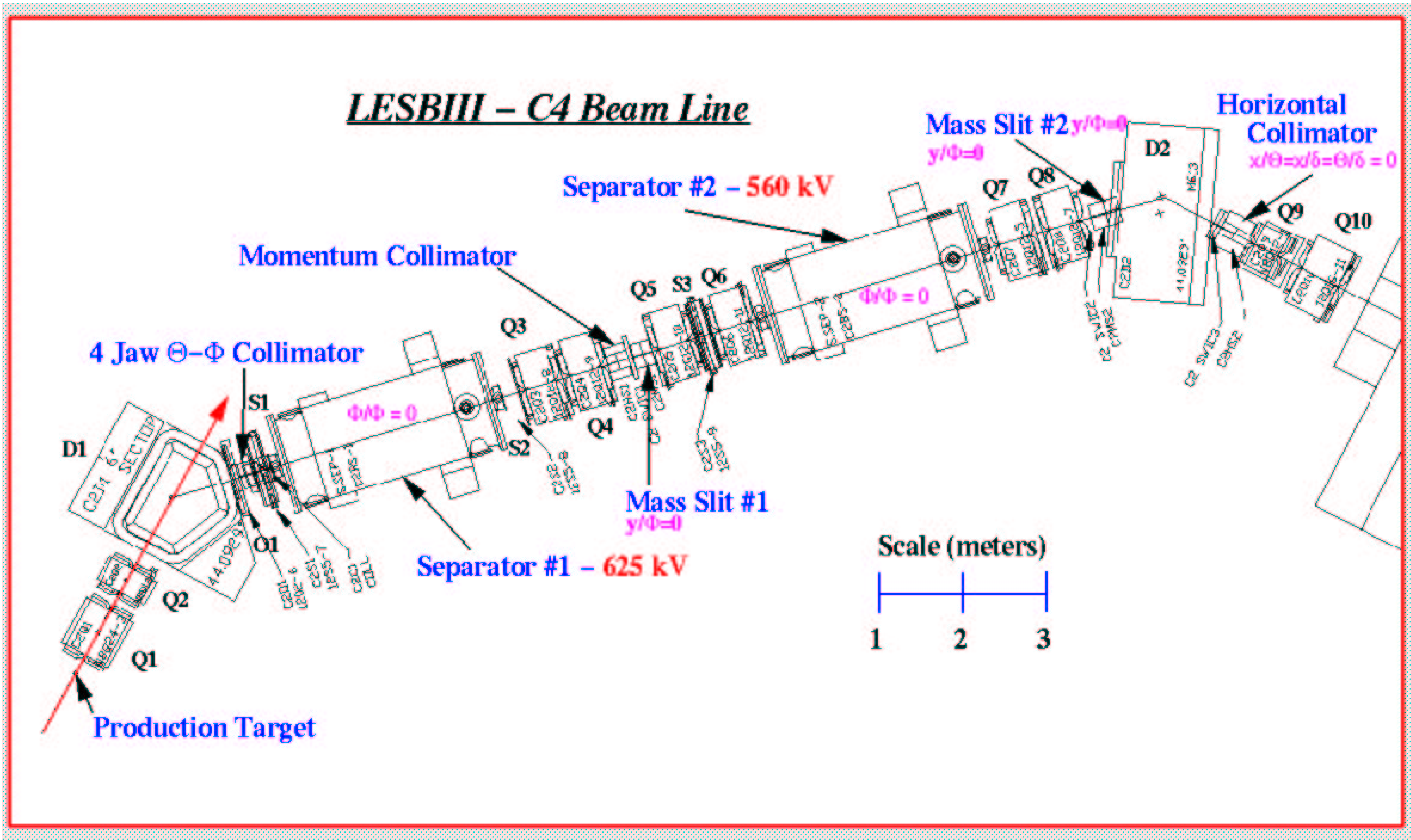
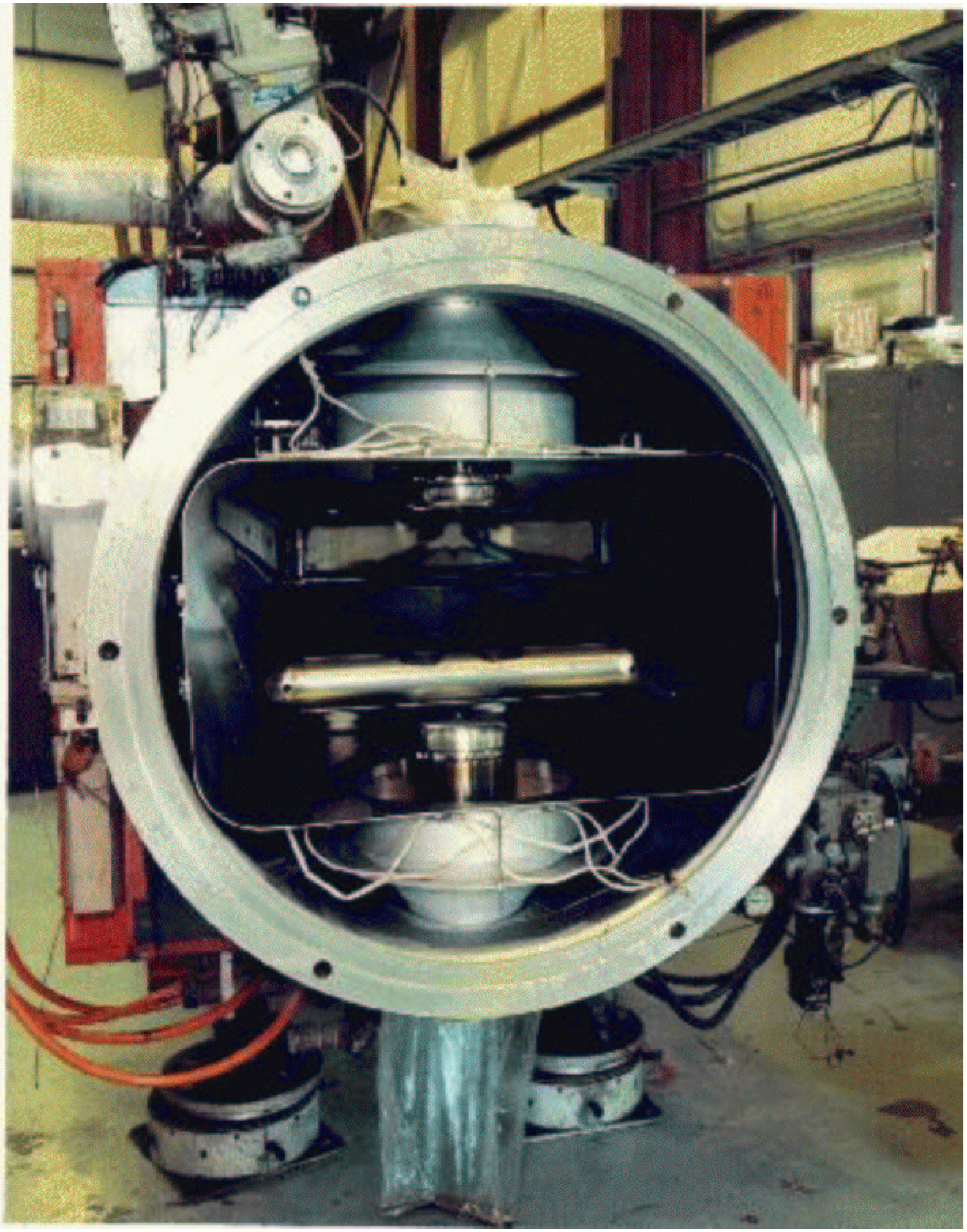

LESBIII – C4 Beam Line
Horizontal Collimator
x/Θ=x/δ=Θ/δ = 0
Mass Slit #2
y/Φ=0
D2
Q7
Q8
Q9
Q10
Separator #2 – 560 kV
Φ/Φ = 0
Momentum Collimator
Q5
S3
Q6
Q3
Q4
4 Jaw Θ–Φ Collimator
S1
D1
Φ/Φ = 0
S2
Mass Slit #1
y/Φ=0
O1
Q2
Q1
Separator #1 – 625 kV
Scale (meters)
1
2
3
Production Target



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E949 collaboration

$>$ 60 physicists, 16 institutes from Canada, Japan, Russia and the US.

V.V. Anisimovsky[7],A.V. Artamonov[6], B. Bassalleck[12], B. Bhuyan[3], E.W. Blackmore[16], D.A. Bryman[16], S. Chen[16], I-H. Chiang[3], I.-A. Christidi[3], P.S. Cooper[4], M.V. Diwan[3], J.S. Frank[3], T. Fujiwara[10], J. Hu[16], A.P. Ivashkin[7], D.E. Jaffe[3], S. Kabe[4], S.H. Kettell[3], M.M. Khabibullin[7], A.N. Khotjantsev[7], P. Kitching[1], M. Kobayashi[4], T.K. Komatsubara[4], A. Konaka[16], A.P. Kozhevnikov[6], Yu.G. Kudenko[7], A. Kushnirenko[4], L.G. Landsberg[6], B. Lewis[12], K.K. Li[3], L.S. Littenberg[3], J.A. Macdonald[16], J. Mildenberger[16], O.V. Mineev[7], M. Miyajima[5], K. Mizouchi[10], V.A. Mukhin[6], N. Muramatsu[10], T. Nakano[14], M. Nomachi[13], T. Nomura[10], T. Numao[16], V.F. Obraztsov[6], K. Omata[4], D.I. Patalakha[6], S.V. Petrenko[6], R. Poutissou[16], E.J. Ramberg[4], G. Redlinger[3], T. Sato[4], T. Sekiguchi[4], T. Shinkawa R.C. Strand[3], S. Sugimoto[4], Y. Tamagawa[5], R. Tschirhart[4], T. Tsunemi[4], D.V. Vavilov[6], B. Viren[3], N.V. Yershov[7], Y. Yoshimura[4] and T. Yoshioka[4]

1. Centre for Subatomic Research, University of Alberta, 2. University of British Columbia, 3. Brookhaven National Laboratory (BNL), 4. Fermi National Accelerator Laboratory (FNAL), 5. Fukui University, 6. Institute for High Energy Physics (IHEP), 7. Institute for Nuclear Research (INR), 8. High Energy Accelerator Research Organization (KEK), 9. Japan Atomic Energy Research Institute (JAERI), 10. Kyoto University, 11. National Defense Academy of Japan, 12. University of New Mexico (UNM), 13. Osaka University, 14. Research Center for Nuclear Physics (RCNP), Osaka University, 15. Stony Brook University and 16. TRIUMF

E949 experimental method

- ~ 700 MeV/c K$^+$ **beam**
- Stop K$^+$ in scint. fiber target
- Wait at least 2 ns for K$^+$ decay
- Measure P in drift chamber
- Measure range R and energy E in target and range stack (RS)
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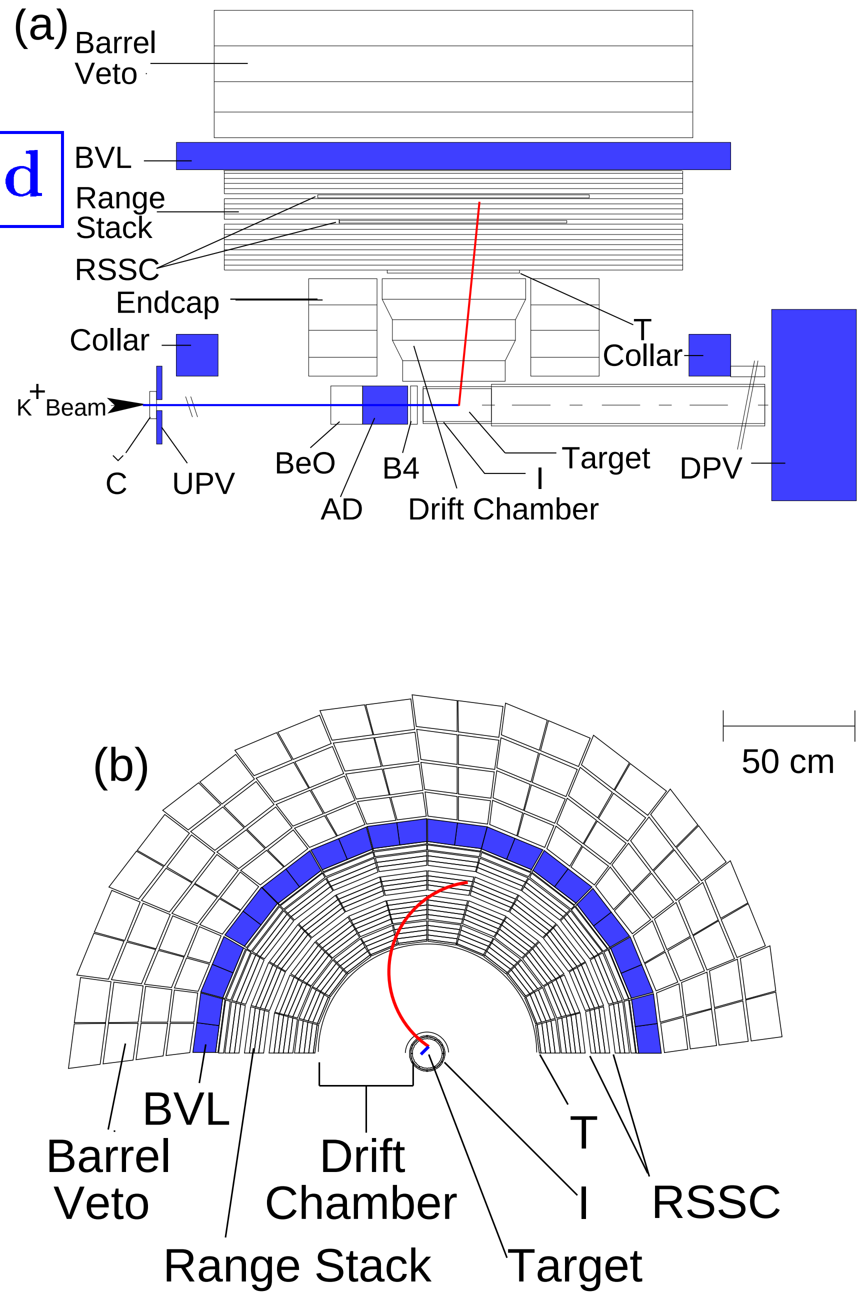
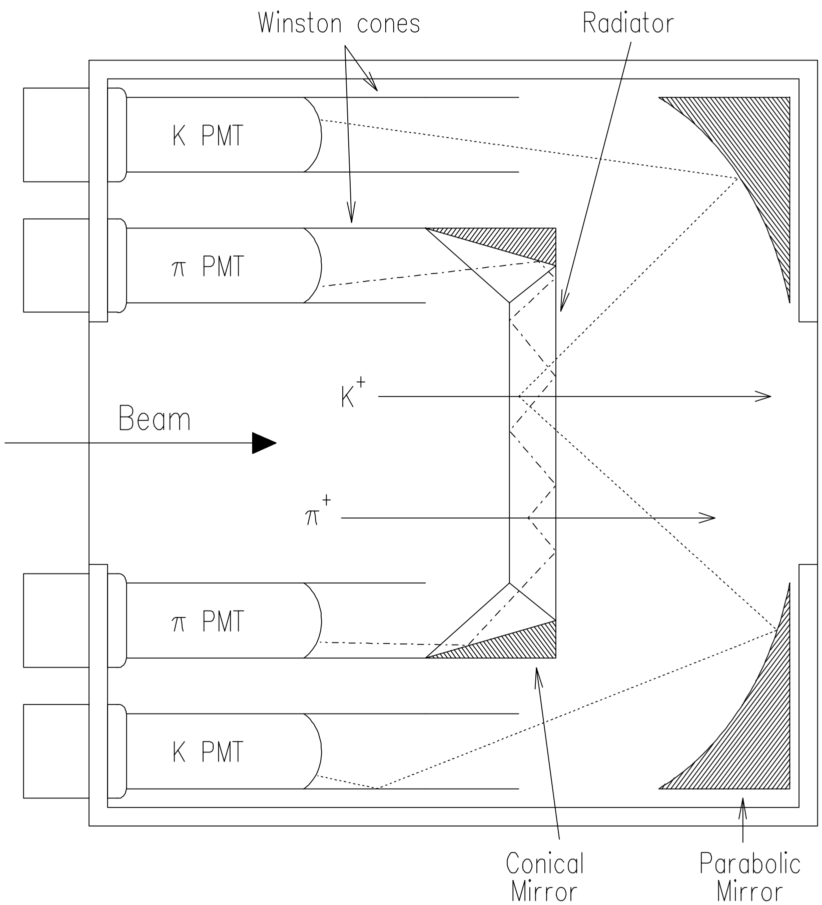
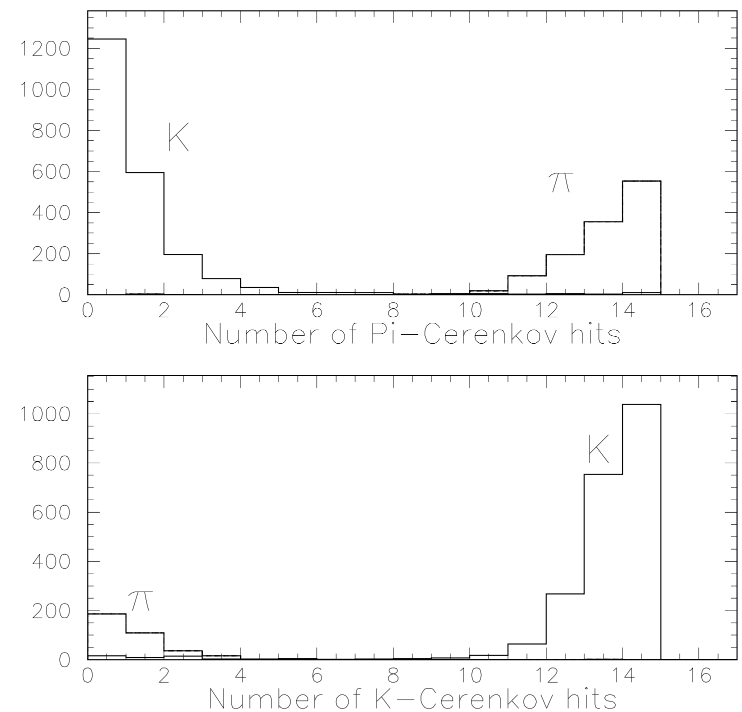
- Observe $\pi^+ \to \mu^+ \to e^+$ in RS
- Veto photons, charged tracks
- **New/upgraded detector elements**




Winston cones
Radiator
K PMT
π PMT
Beam
K+
π+
π PMT
K PMT
Conical Mirror
Parabolic Mirror


K
π
Number of Pi−Cerenkov hits
π
K
Number of K−Cerenkov hits

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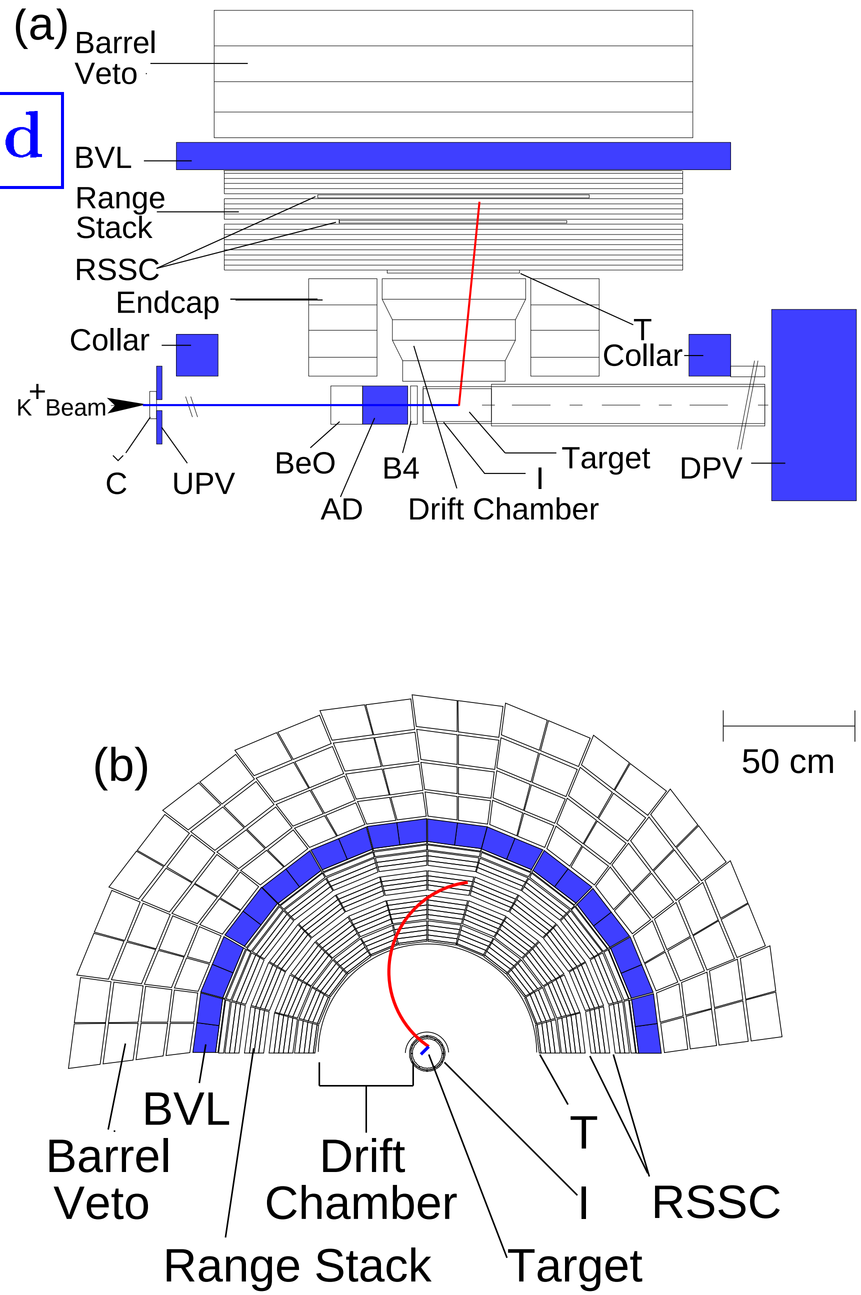

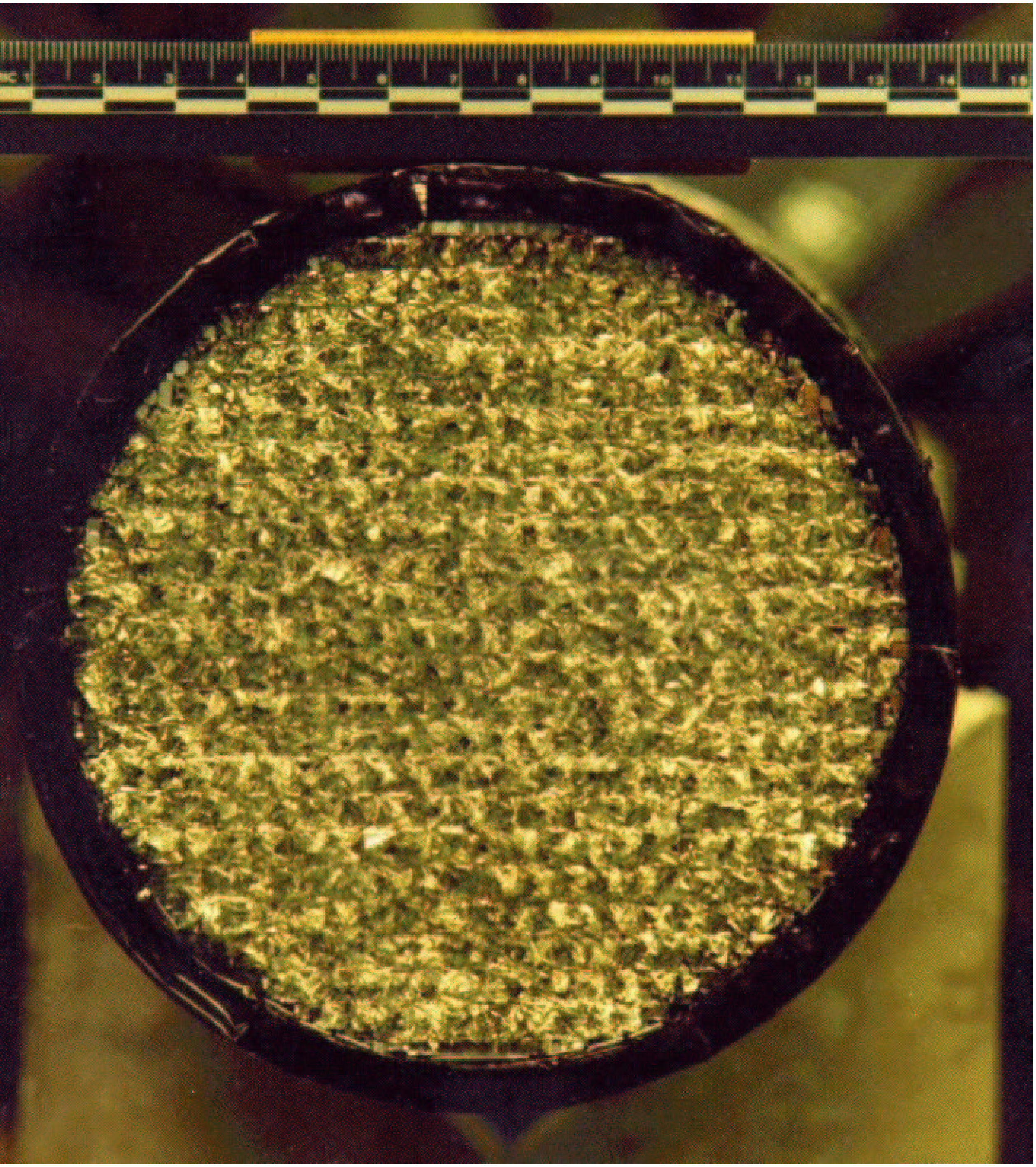

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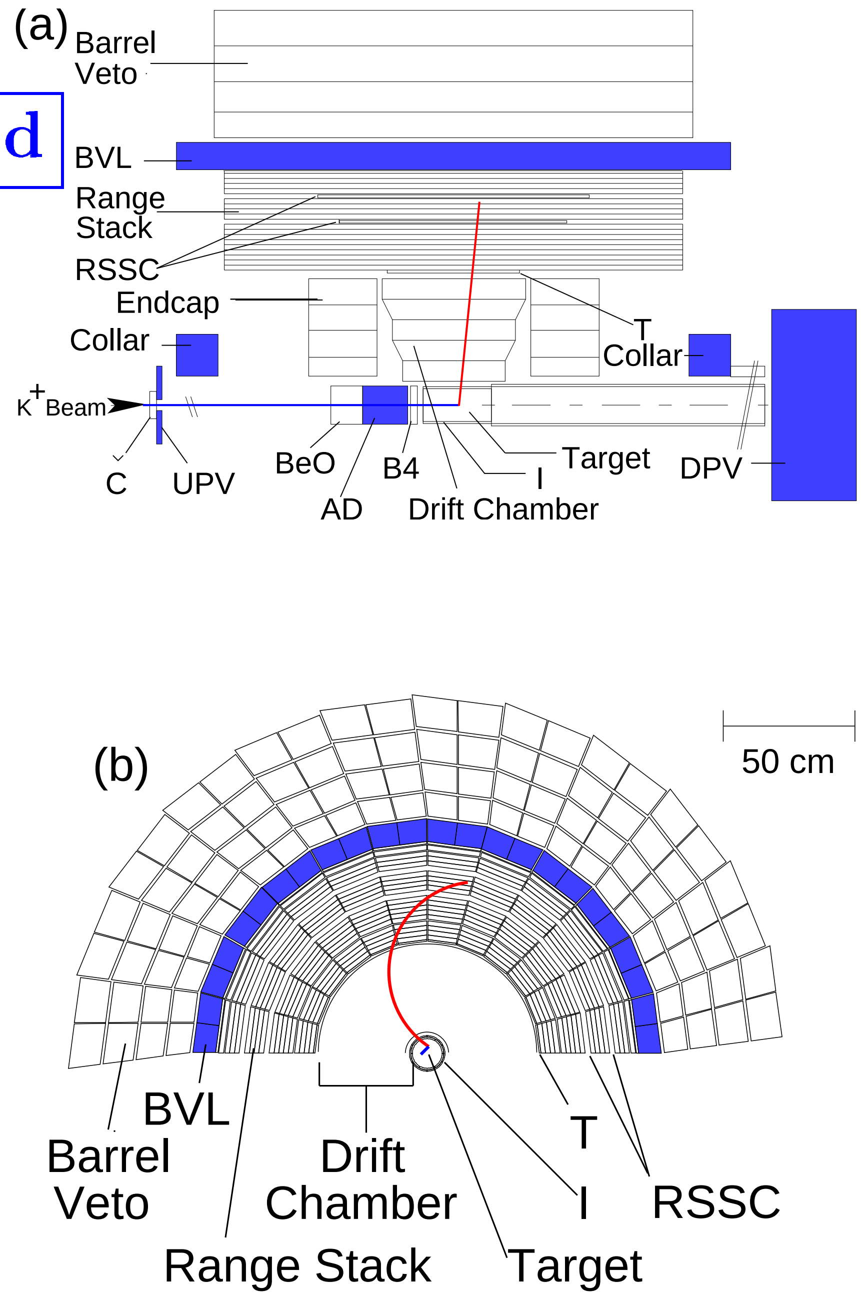

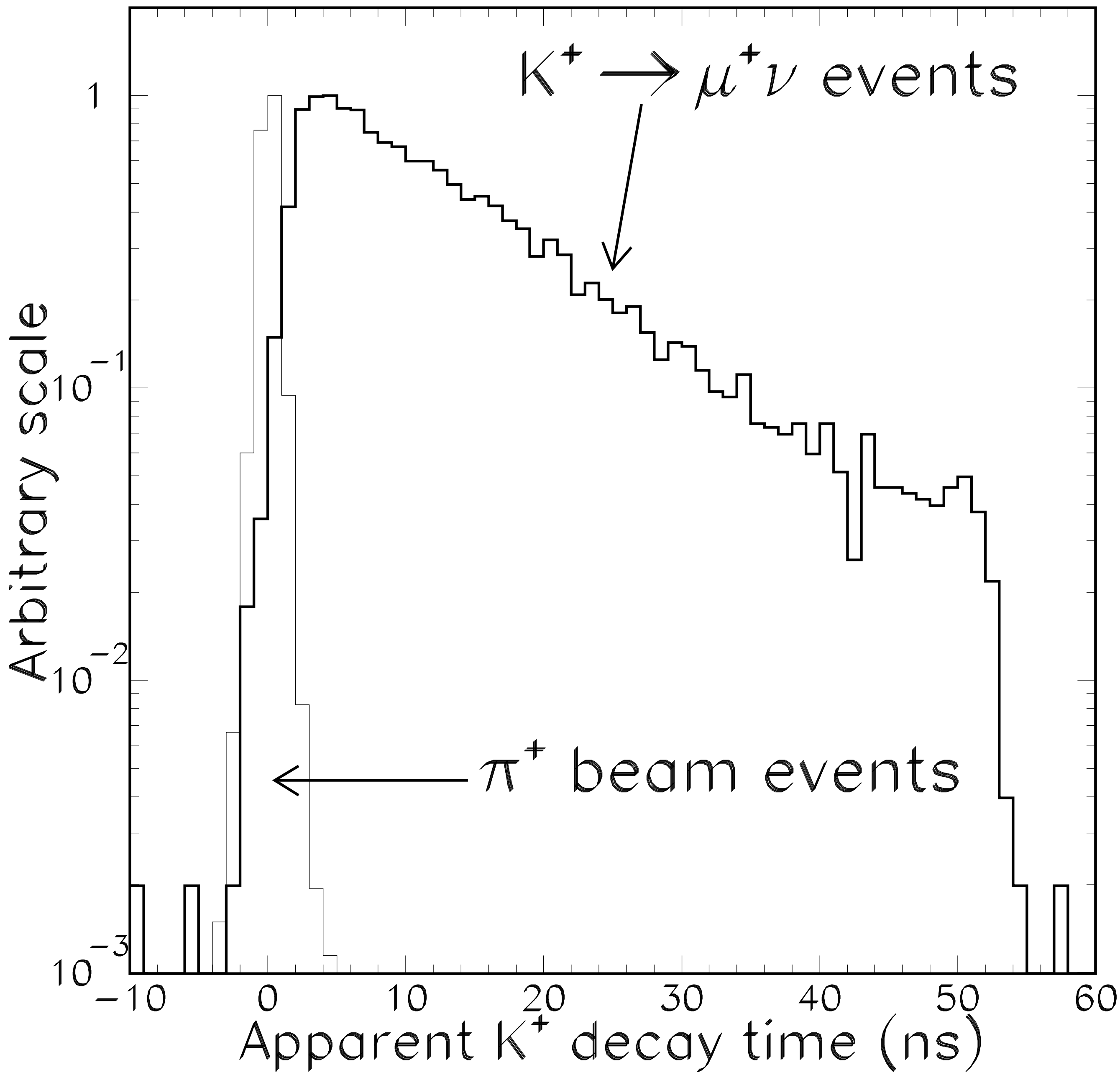

$K^+ \longrightarrow \mu^+\nu$ events
π^+ beam events
Arbitrary scale
1
10^{-1}
10^{-2}
10^{-3}
−10
0
10
20
30
40
50
60
Apparent K^+ decay time (ns)

E949 experimental method

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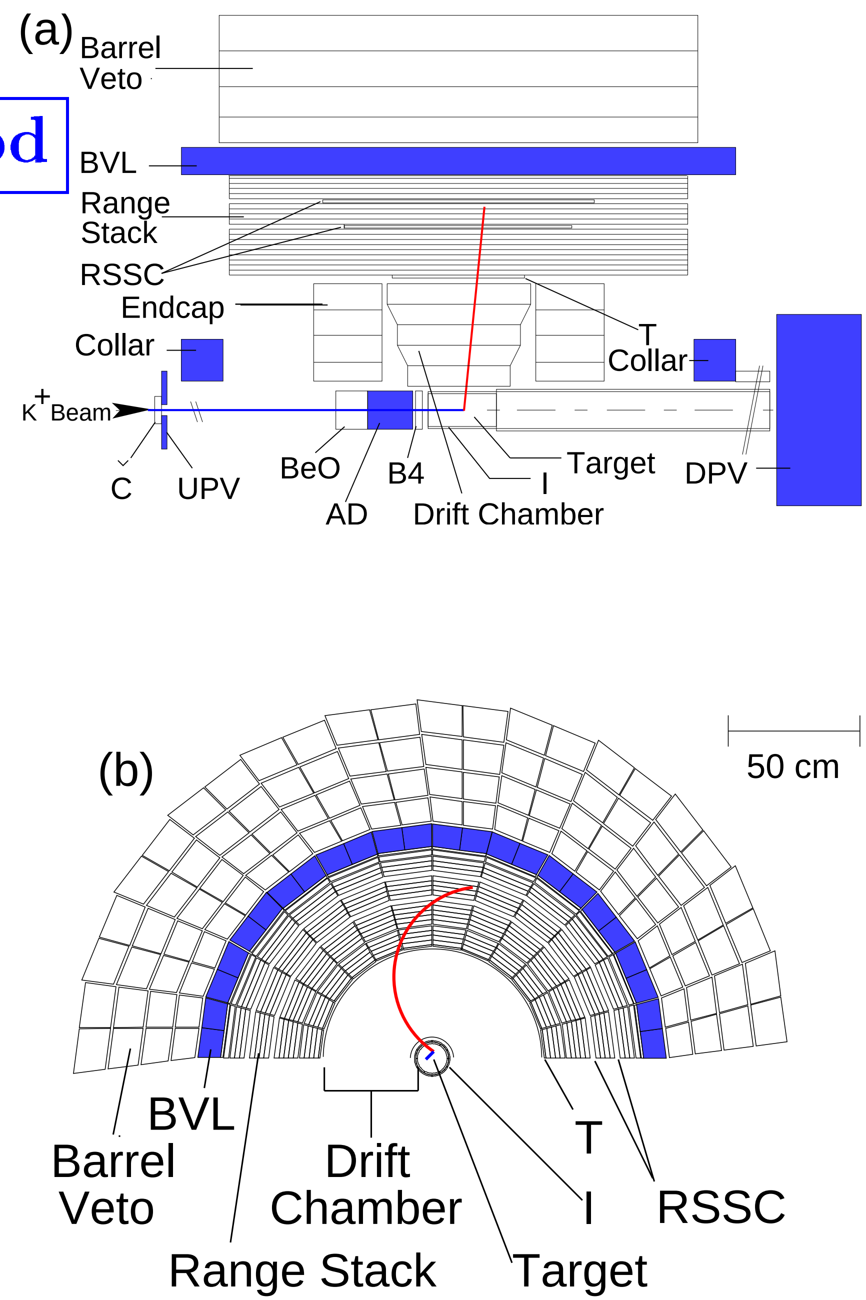

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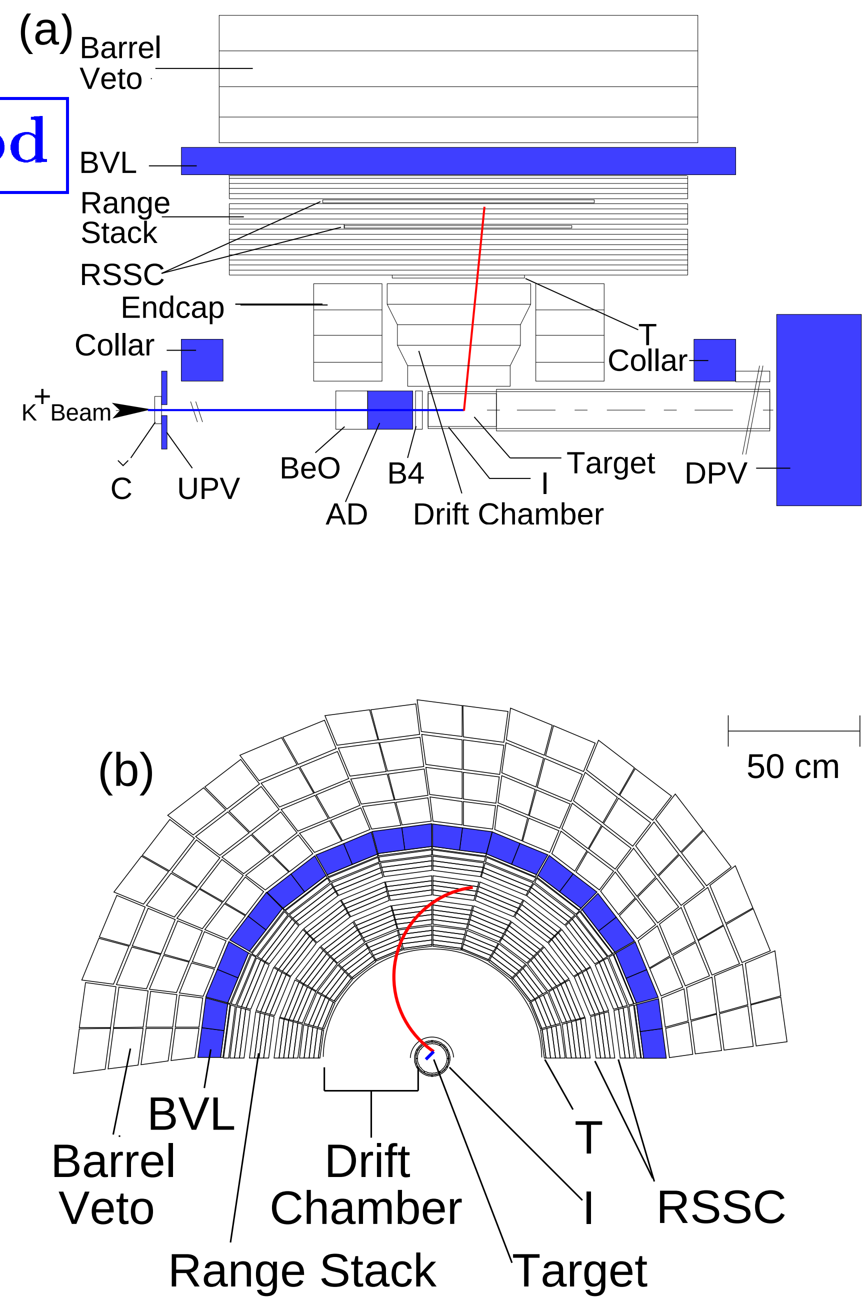

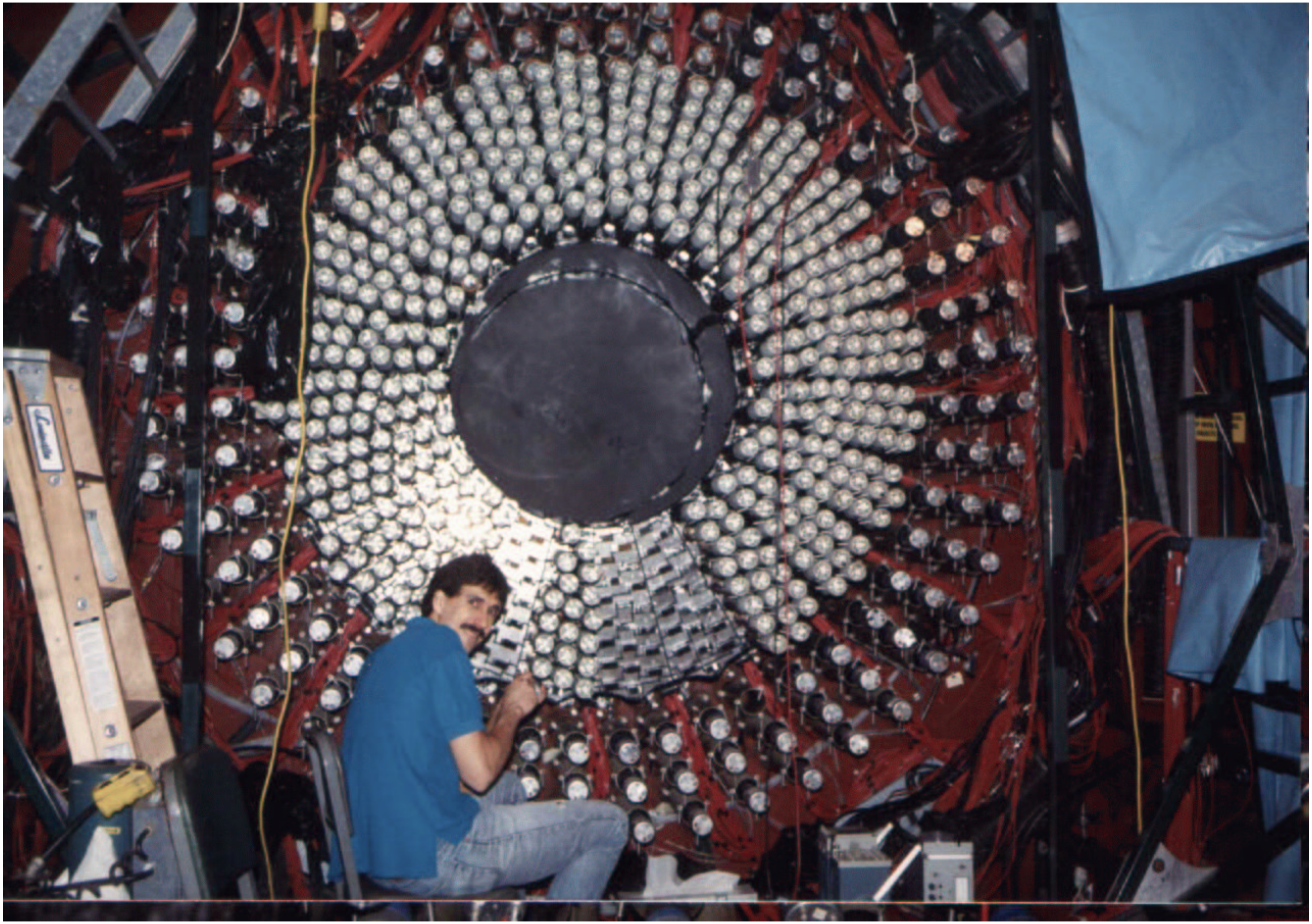

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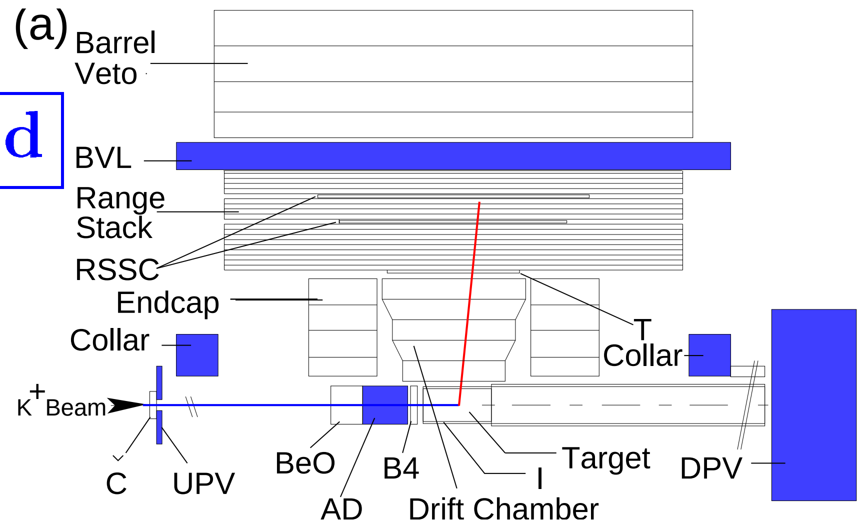
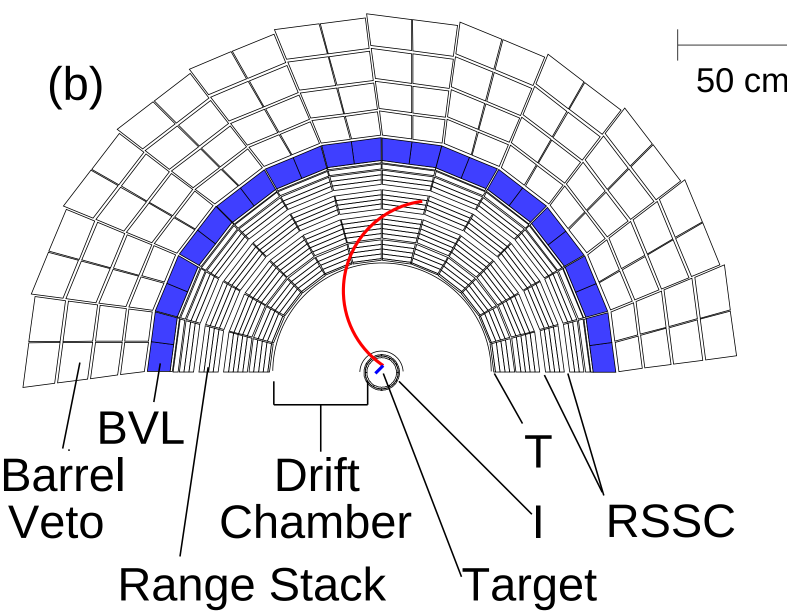
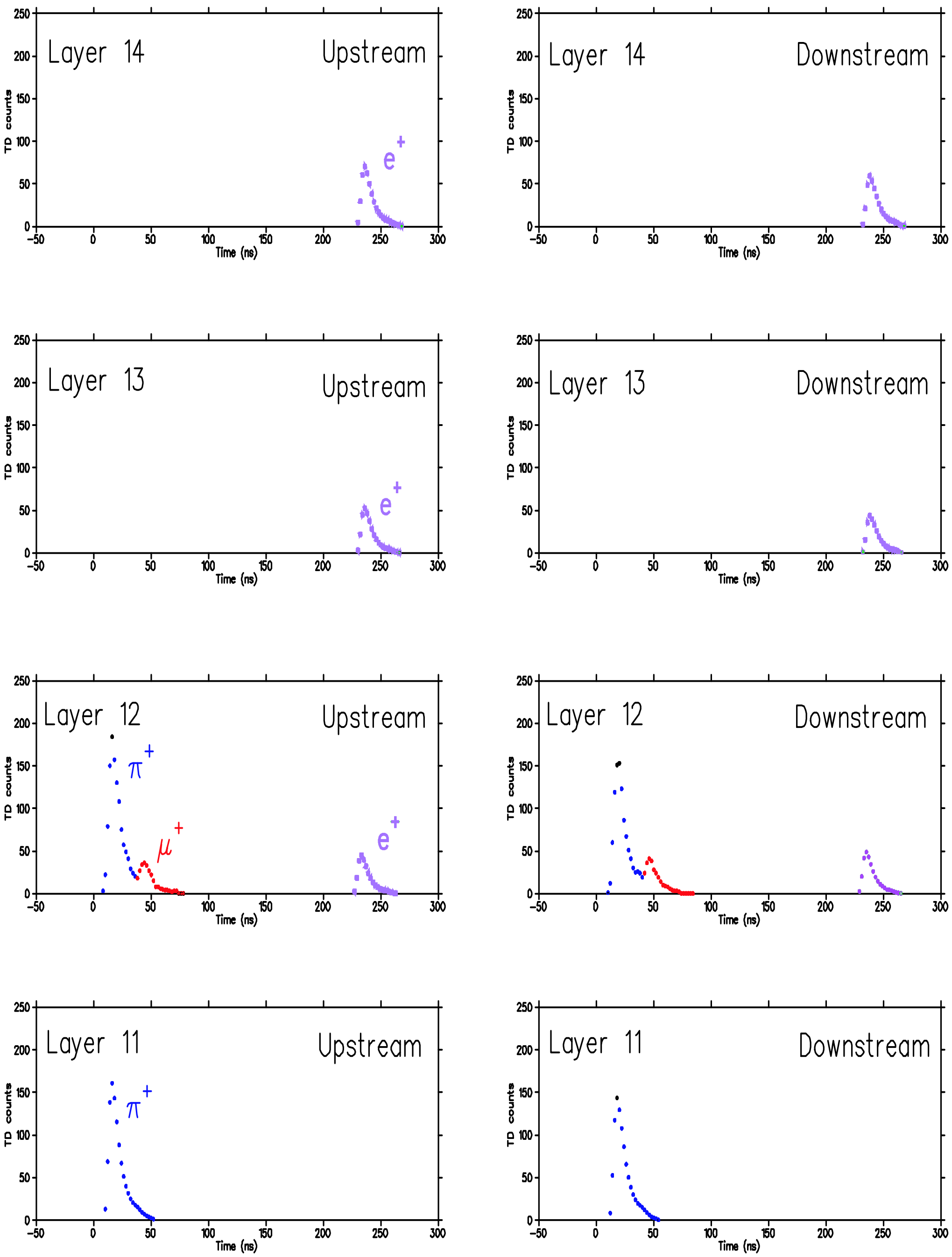






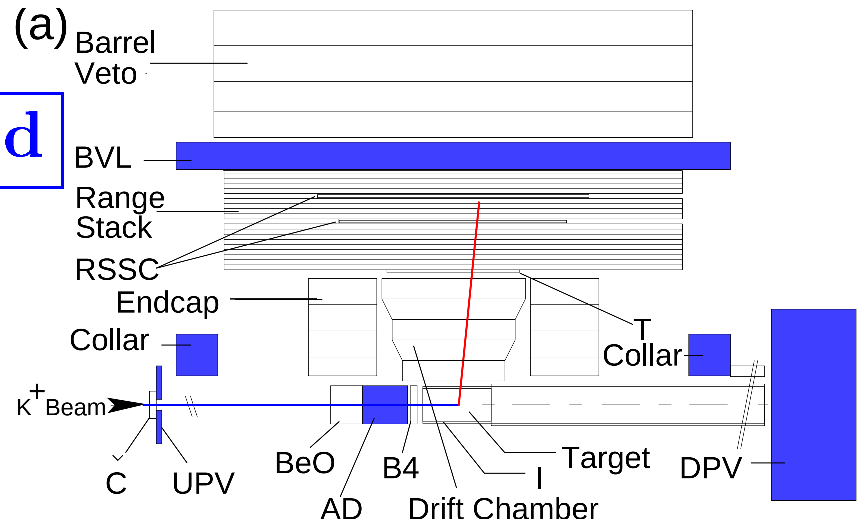
Identifying $\pi^+ \to \mu^+ \to e^+$

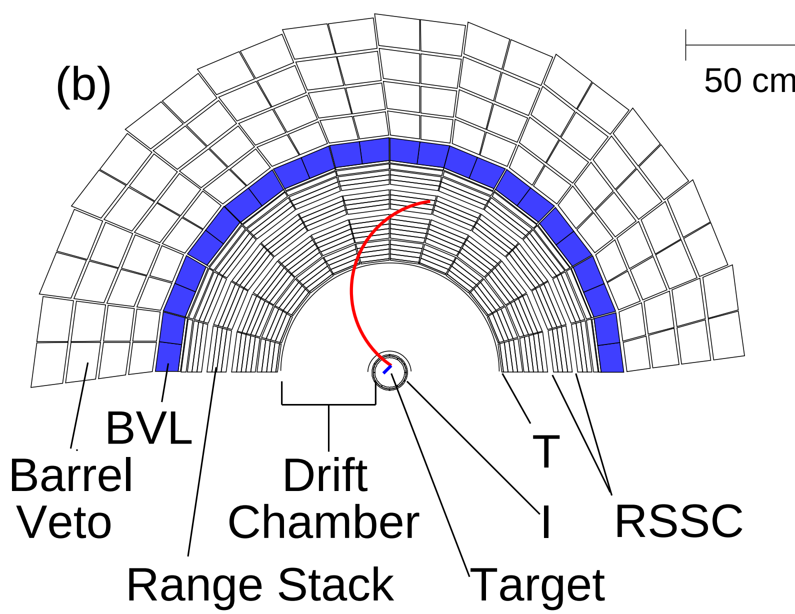
- Sample pulse height every 2 ns for 2 μs (TDCs to 10 μs)
- π^+ stops in range stack scintillator (2 cm/layer)
- $\pi^+ \to \mu^+ \nu$, $E_\mu = 4.1$ MeV, $R_\mu \sim 1$ mm, $\tau_\pi = 26.0$ ns
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$, $E_e \leq 53$ MeV, $\tau_\mu = 2.20$ μs

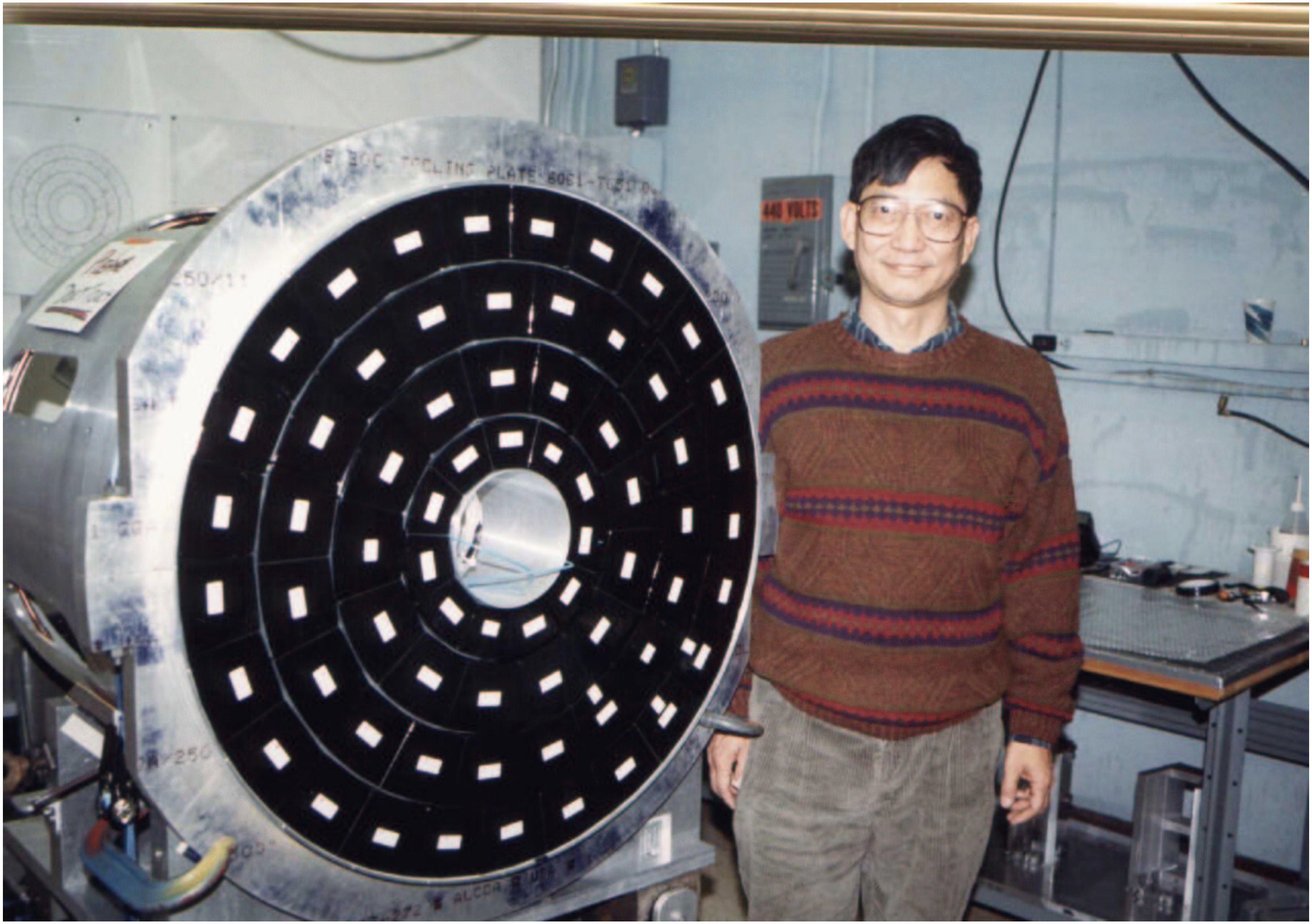
Plots: Pulse height (0 to 250) *vs* time (-50 to 300 ns)

E949 experimental method

- ~ 700 MeV/c K^+ beam
- Stop K^+ in scint. fiber target
- Wait at least 2 ns for K^+ decay
- Measure P in drift chamber
- Measure range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in RS
- **Veto photons, charged tracks**
- **New/upgraded detector elements**



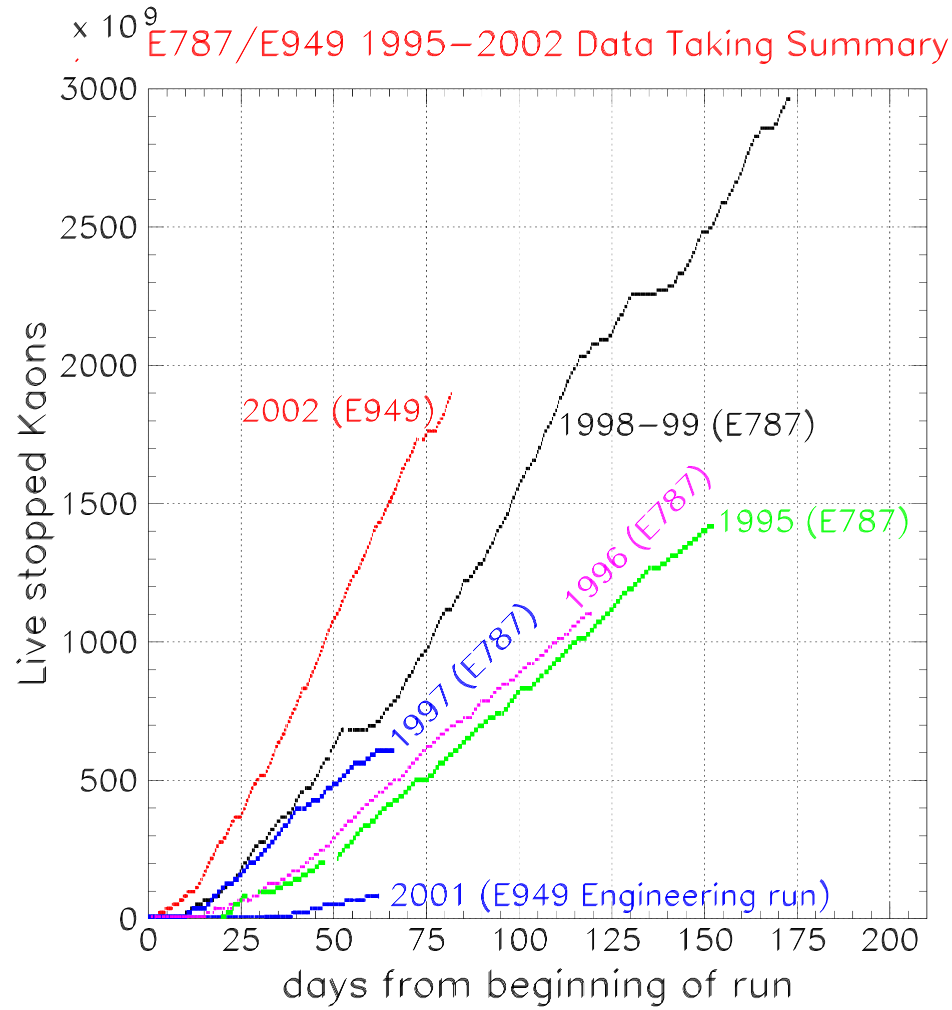



440 VOLTS

E949 status for 2002 data taking

Upgrades to E787:

- More protons/sec from AGS
- Improved photon veto hermeticity
- Improved tracking and energy resolution
- Higher rate capability due to DAQ and trigger improvements



Not optimal in 2002:

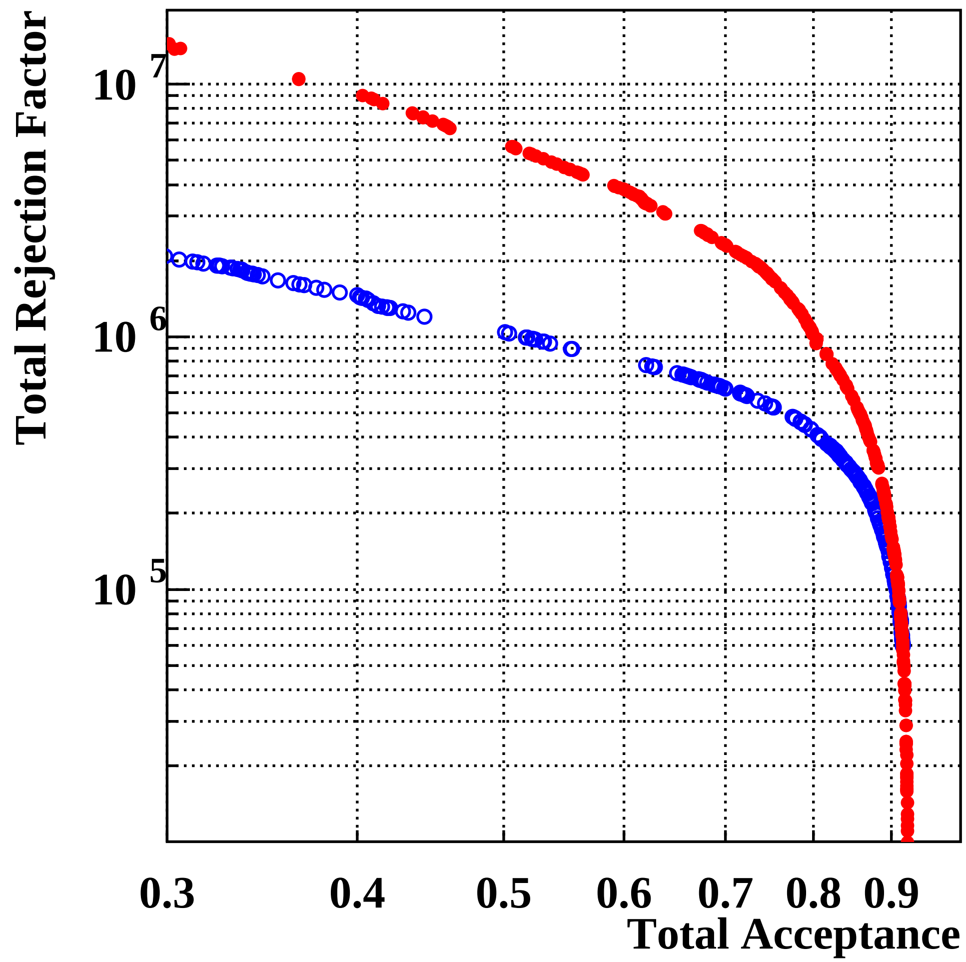
1. Spill duty factor.
2. Proton beam momentum.
3. K/π electrostatic separators.

E949: Upgrade of photon veto

Improved photon veto hermeticity.

Figure: background **Rejection** as a function of $K^+ \to \pi^+ \nu \bar{\nu}$ signal **Acceptance** for the photon veto cut for E787 and E949.

$\sim$ 2$\times$ better rejection at nominal **PNN1** acceptance of 80% *or* $\sim$ 5% more acceptance in E949 with same rejection as E787.



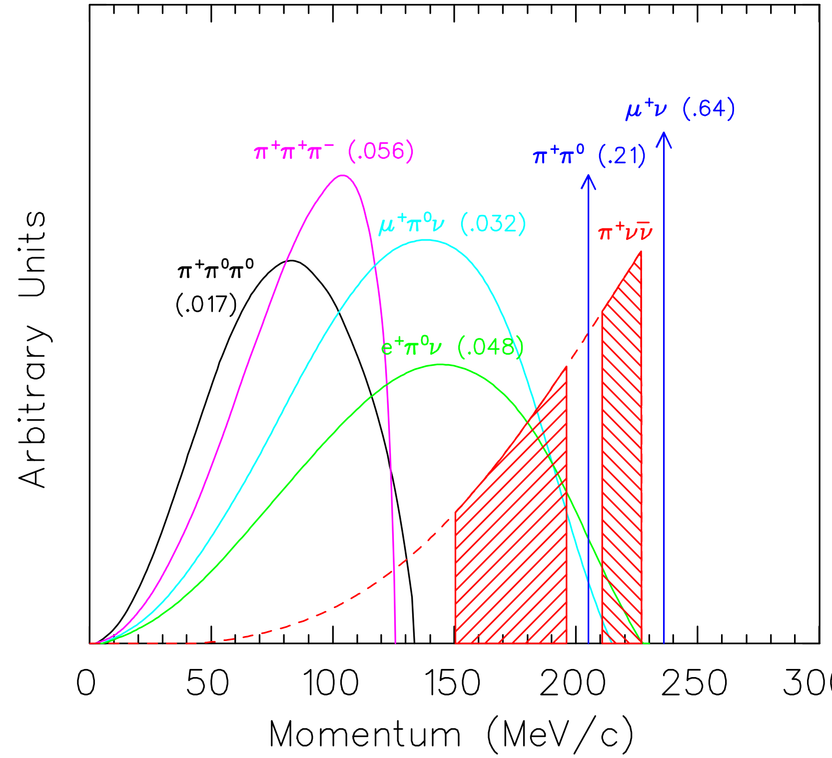
E787 and E949 analysis strategy

- **A priori identification of background sources.**
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(\mathrm{K}^+ \to \pi^+\pi^0)$.
- "Blind" analysis. Don't examine signal region until all backgrounds verified.

$K^+ \to \pi^+\nu\bar{\nu}$ and background rates

Process	Rate
$K^+ \to \pi^+\nu\bar{\nu}$	0.77×10^{-10}
$K^+ \to \pi^+\pi^0$	$2113000000.00 \times 10^{-10}$
$K^+ \to \mu^+\nu$	$6343000000.00 \times 10^{-10}$
$K^+ \to \mu^+\nu\gamma$	$55000000.00 \times 10^{-10}$
$K^+ \to \pi^0\mu^+\nu$	$327000000.00 \times 10^{-10}$
CEX	$\sim 46000.00 \times 10^{-10}$
Scattered π^+ beam	$\sim 25000000.00 \times 10^{-10}$

π^+ momentum in K^+ rest fram



CEX $\equiv (K^+ n \to K^0 X) \times (K^0 \to K^0_L) \times (K^0_L \to \pi^+\ell^-\nu)$

ℓ^- is μ^- or e^-

$K^+ n \to K^0 X$ rate is empirically determined.

E787 and E949 analysis strategy

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Background suppression

Source	Suppresion method			
	Kinematics	Particle ID	Veto	Timing
$\mathrm{K}^+ \to \mu^+\nu(\gamma)$ ($\mathrm{K}_{\mu 2}$)	$\surd$	$\surd$	($\surd$)	
$\mathrm{K}^+ \to \pi^+\pi^0$ ($\mathrm{K}_{\pi 2}$)	$\surd$		$\surd$	
Scattered π^+ beam		$\surd$		$\surd$
CEX			$\surd$	$\surd$

$\mathrm{CEX} \equiv \mathrm{K}^+ n \to K^0 p\ ,\ K^0_L \to \pi^+\ell^-\nu$

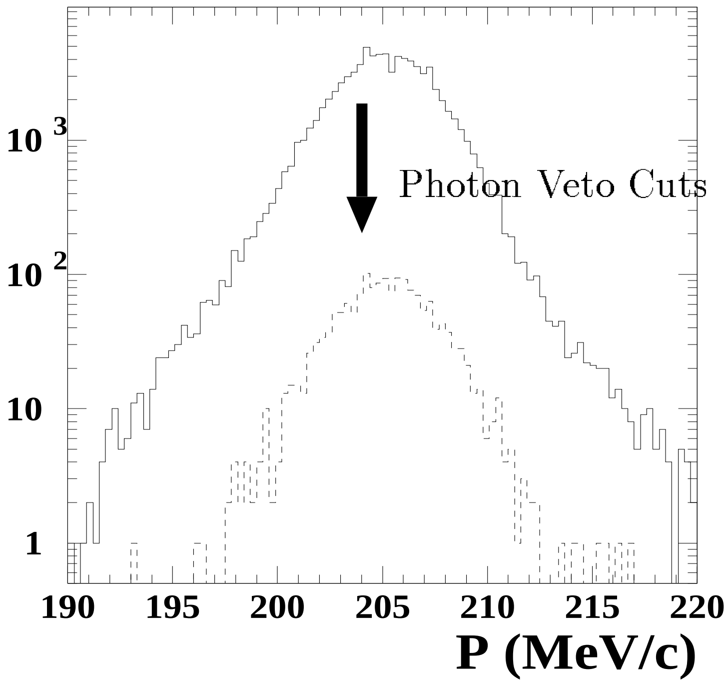
Particle ID includes beam Cherenkov, dE/dx and $\pi \to \mu \to e$ detection

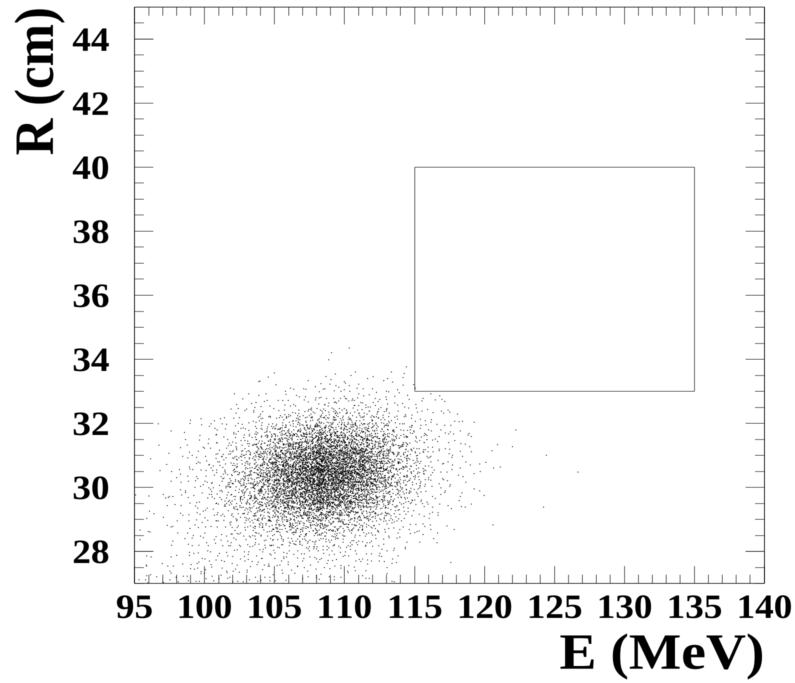
Veto includes both photon and charged particle vetoing

E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- **Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.**
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(\mathrm{K}^+ \to \pi^+\pi^0)$.
- "Blind" analysis. Don't examine signal region until all backgrounds verified.

Example: $K^+ \to \pi^+\pi^0$ background rejection





Left: Kinematically selected $K^+ \to \pi^+\pi^0$ with photon veto applied. Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

Right: Select photons. Phase space cuts in P, R, E.

E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
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- **Verify background estimates by loosening cuts and comparing observed and predicted rates.**
- Use MC to measure geometrical acceptance for $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(\mathrm{K}^+ \to \pi^+\pi^0)$.
- "Blind" analysis. Don't examine signal region until all backgrounds verified.

Verify background by loosening cuts

Define rejection power $\equiv 1$ when cuts are set to produce pre-determined signal region ("signal box")

Relax cut to reduce rejection by $\times 10$. New, larger region should have $10\times$ background of signal box.

Example: For $K^+ \to \pi^+\pi^0$ background, simultaneously loosen photon veto (PV) and kinematic (KIN) cuts each by $\times 10$. Expect $10 \times 10 = 100$ times more background than that of the signal box.

Compare background prediction with observation near signal region

	PV×KIN	10×10	20×20	20×50	50×50	50×100
$K_{\pi 2}$	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
	TD×KIN	10×10	20×20	50×50	80×50	120×50
$K_{\mu 2}$	Observed	0	1	12	16	25
	Predicted	0.35	1.4	9.1	14.5	21.8
	TD×KIN	10×10	20×20	50×20	80×20	80×40
$K_{\mu m}$	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4

$K_{\pi 2} \equiv K^+ \to \pi^+\pi^0$; $K_{\mu 2} \equiv K^+ \to \mu^+\nu$;

$K_{\mu m} \equiv K^+ \to \mu^+\nu\gamma$, $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \pi^+\pi^0$ with $\pi^+ \to \mu^+\nu$ decay in flight

TD$\equiv \pi \to \mu \to e$ identification, PV≡Photon Veto rej., KIN≡ kinematic rej.
$M \times N \equiv$ reduction in rejection with respect to signal region

Compare background prediction with observation near signal region

Quantify consistency: Fit $N_{\text{obs}} = cN_{\text{pred}}$ and expect $c = 1$.

Background	c	χ^2 Probability	Total background
$\mathrm{K}_{\pi 2}$	$0.85^{+0.12}_{-0.11}$	0.17	0.216 ± 0.023
$\mathrm{K}_{\mu 2}$	$1.15^{+0.25}_{-0.21}$	0.67	0.044 ± 0.005
$\mathrm{K}_{\mu m}$	$1.06^{+0.35}_{-0.29}$	0.40	0.024 ± 0.010

Deviation of c from unity is taken into account in evaluation of $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$

Beam and CEX background is 0.014 ± 0.003

The calculated number of background events in the signal region is 0.30 ± 0.03 from all background sources.

E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- **Use MC to measure geometrical acceptance for $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(\mathrm{K}^+ \to \pi^+\pi^0) = 0.215 \pm 0.005$. World average value is 0.2113 ± 0.0014.**
- "Blind" analysis. Don't examine signal region until all backgrounds verified.

E949 improved analysis strategy†

1. E787 background estimation methods are reliable
2. Divide signal region into cells and calculate background (b_i) and signal acceptance (s_i) for each cell. Example: Tighten PV cut to select subregion with 1/10 of the total predicted $\mathrm{K}^+ \to \pi^+\pi^0$ background within "signal box"
3. Can calculate $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ using s_i/b_i of any cells containing candidates using likelihood ratio method.
4. Increase total size of signal region to increase acceptance at cost of more total background

† With age comes wisdom.

E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+\pi^0)$.
- **"Blind" analysis. Don't examine signal region until all backgrounds verified.**

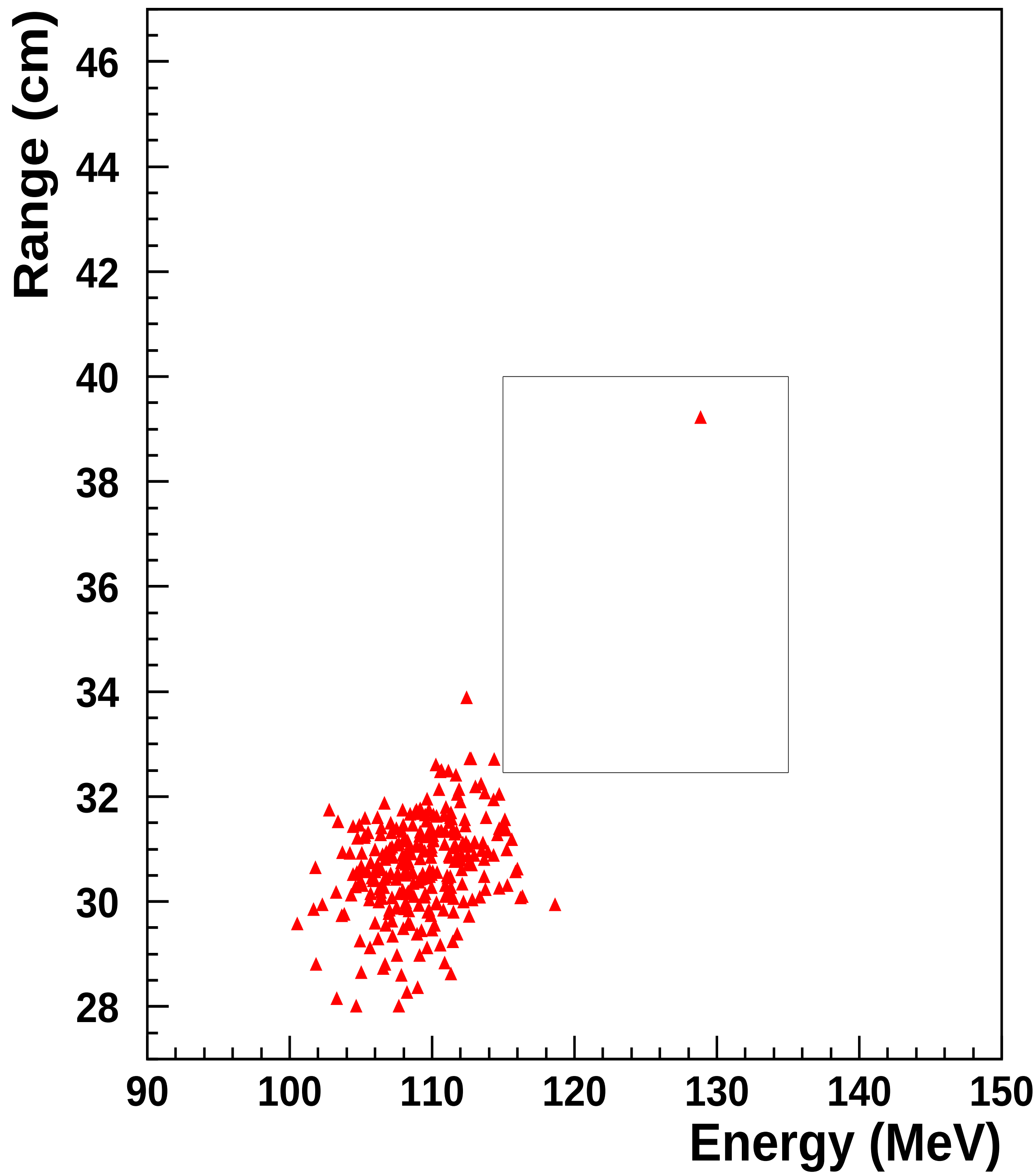
Opening the box

Range (cm) *vs* Energy (MeV) for E949 data after all other cuts applied.

Solid line shows signal region.

Single candidate found.

Cluster near 110 MeV is unvetoed $K^+ \rightarrow \pi^+\pi^0$.



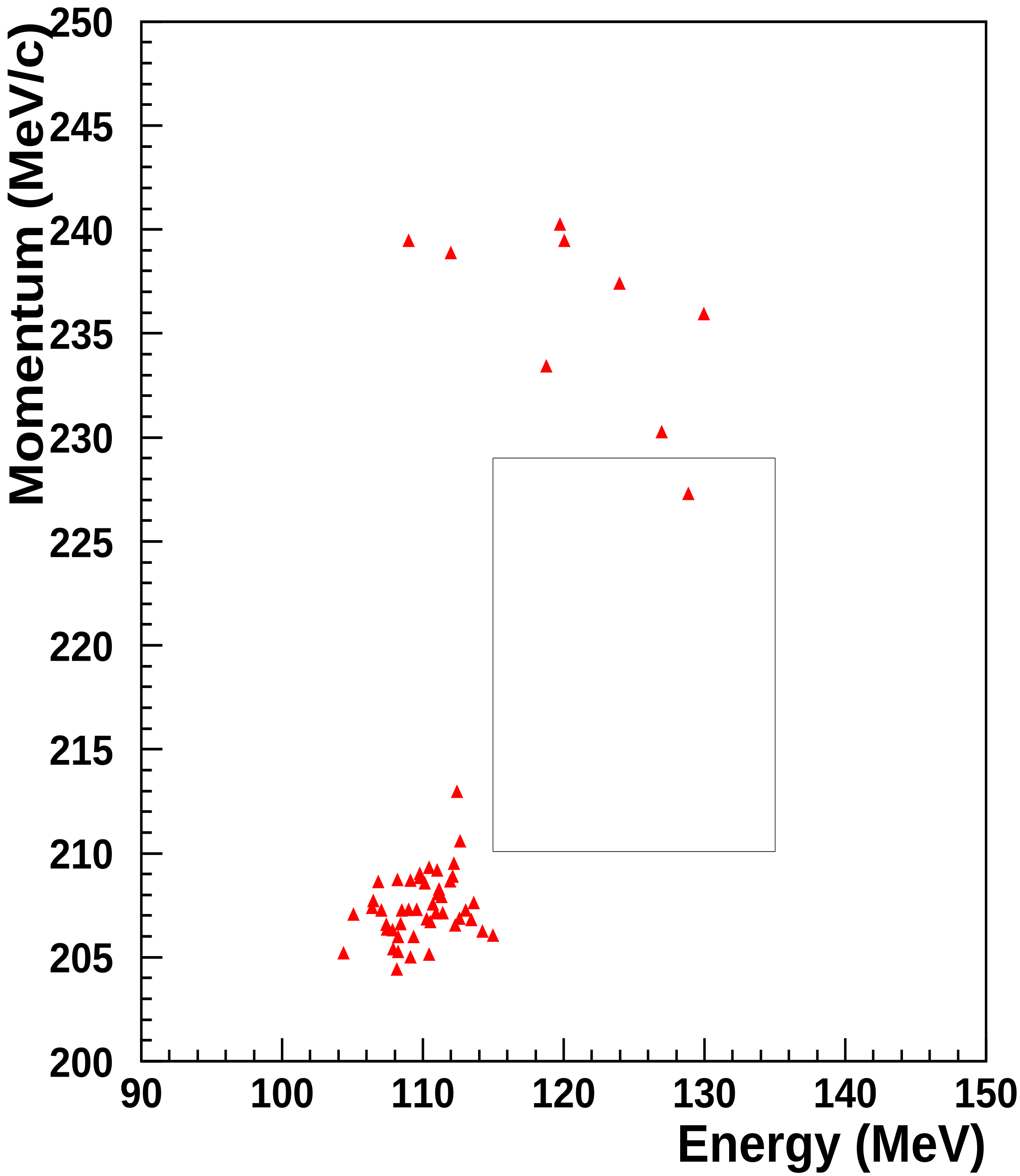
Same candidate, different variables.

Momentum (MeV/c) *vs* Energy (MeV/c) for E949 data after all other cuts applied.

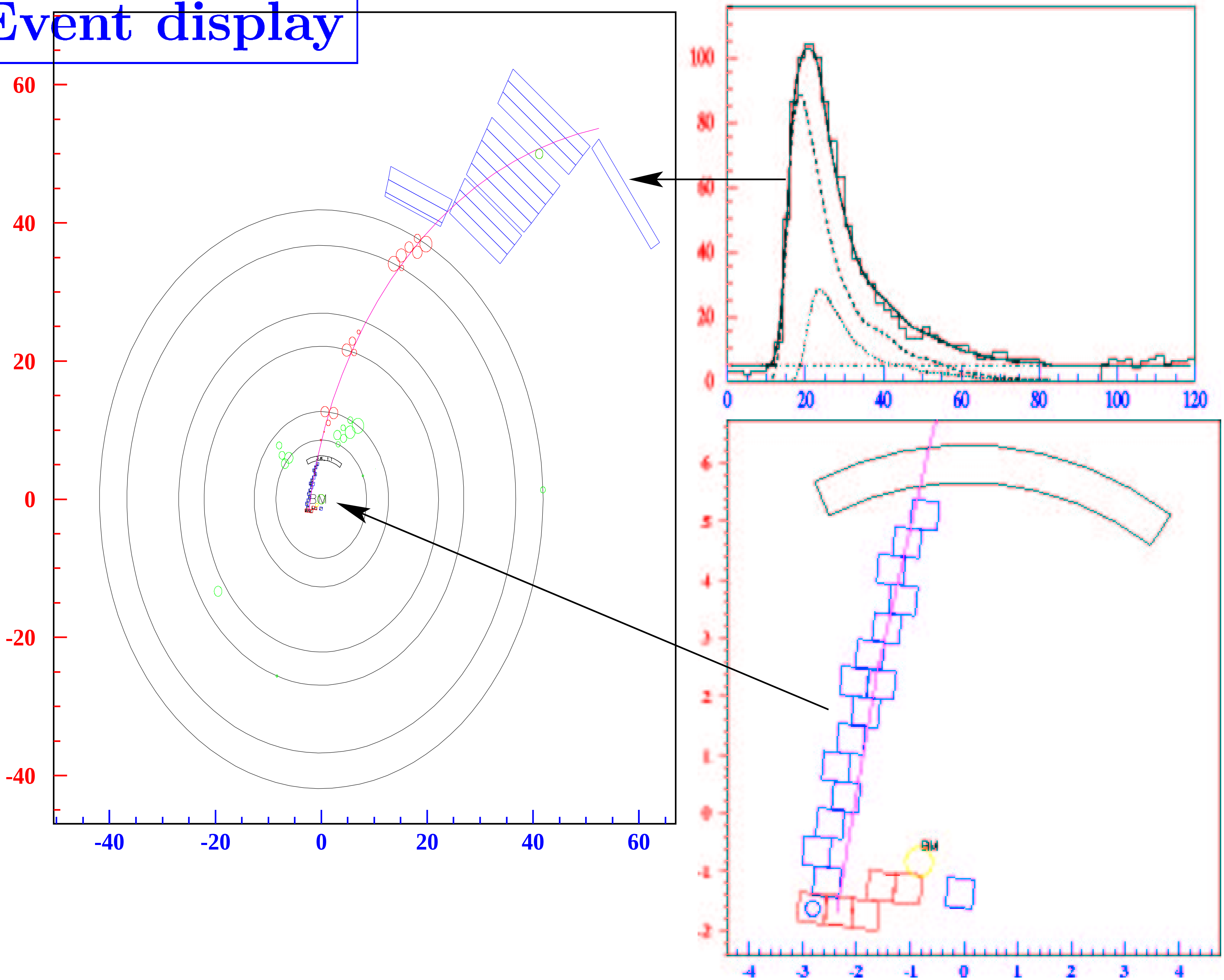
Solid line shows signal region.

Events above signal region are unvetoed $K^+ \to \mu^+ X$

Cluster near 110 MeV is unvetoed $K^+ \to \pi^+ \pi^0$.



Event display



How likely is it that the candidate is due to known background?

Question: Suppose we do 100 experiments, how many will have a candidate from a known background source that is as signal-like or more signal-like than the observed candidate?

Answer: ~ 7

The sum of background in all cells with s_i/b_i greater or equal to the cell containing the observed candidate is 0.077. The probability that 0.077 could produce one or more events is 0.074 ($\sim 7/100$).

The E949 candidate is more likely to be due to background than the two E787 candidates.

Candidate	E787A	E787C	E949A
Probability	0.006	0.02	0.07

	E787		E949
Stopped K^+ (N_K)	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
W_i	0.98	0.88	0.48

b_i = background of cell containing candidate

$S_i \equiv \mathcal{B} A_i N_K$ = signal for cell containing candidate

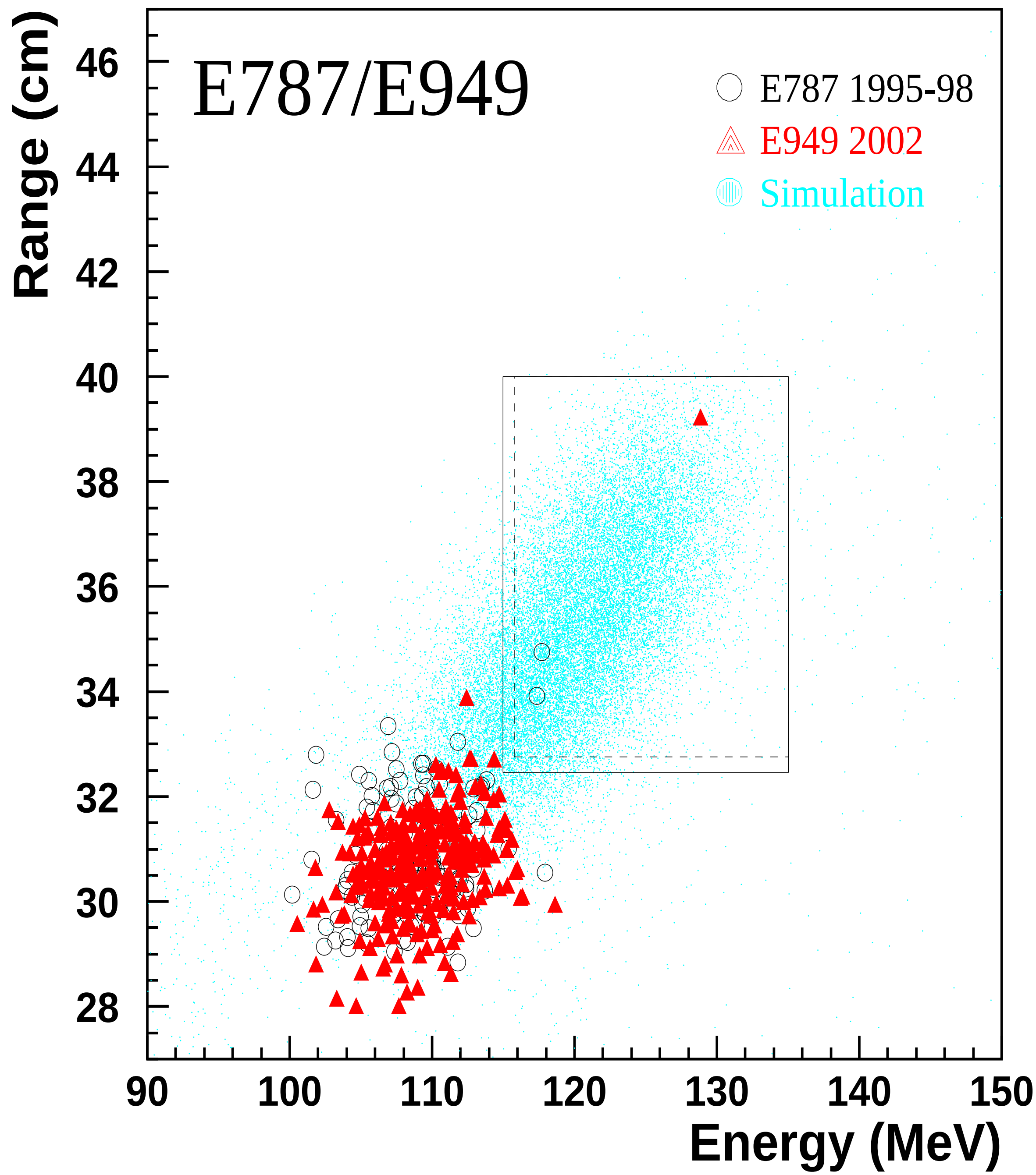
$A_i \equiv$ acceptance

$\mathcal{B}$ = measured central value of $K^+ \to \pi^+ \nu\bar{\nu}$ branching fraction

$W_i \equiv S_i/(S_i + b_i)$ = event weight

Event weight W_i and S_i/b_i assumes SM signal hypothesis as well as calculated background.

Range (cm) *vs* Energy (MeV) for combined E787 and E949 data after all other cuts applied.
Dashed line is E787 signal region.
Solid line is E949 signal region.



Combined E787 and E949 results for $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$

$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\overline{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ (68%CL interval)

$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\overline{\nu}) > 0.42 \times 10^{-10}$ at 90%CL.

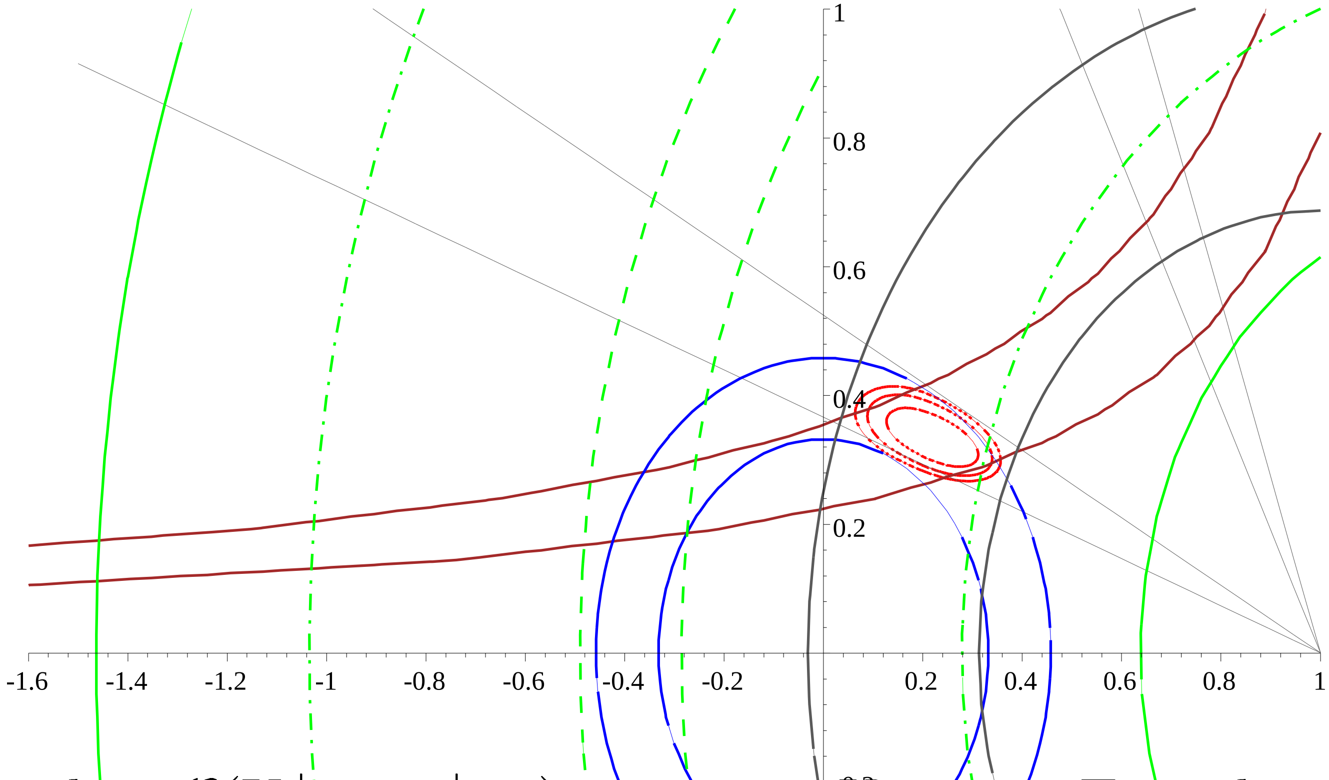
SM prediction†: $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$

The probability that background alone gave rise to the three observed events or to any more signal-like configuration is 0.001.

E787 result: $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\overline{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$

† Reference: Buchalla& Buras, NP**B548** 309 (1999); Isidori, hep-ph/0307014;Buras, hep-ph/0402112

Impact of $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ on Unitarity Triangle

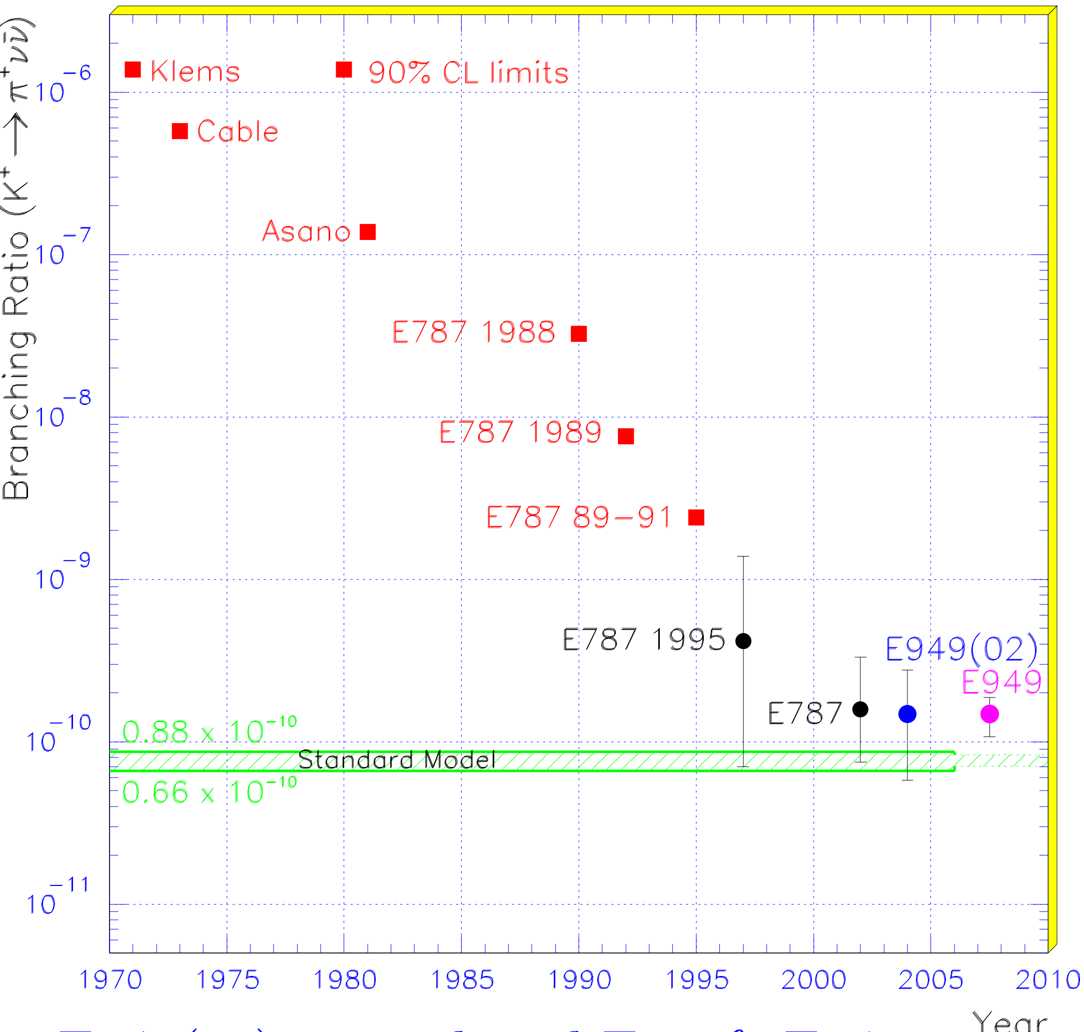


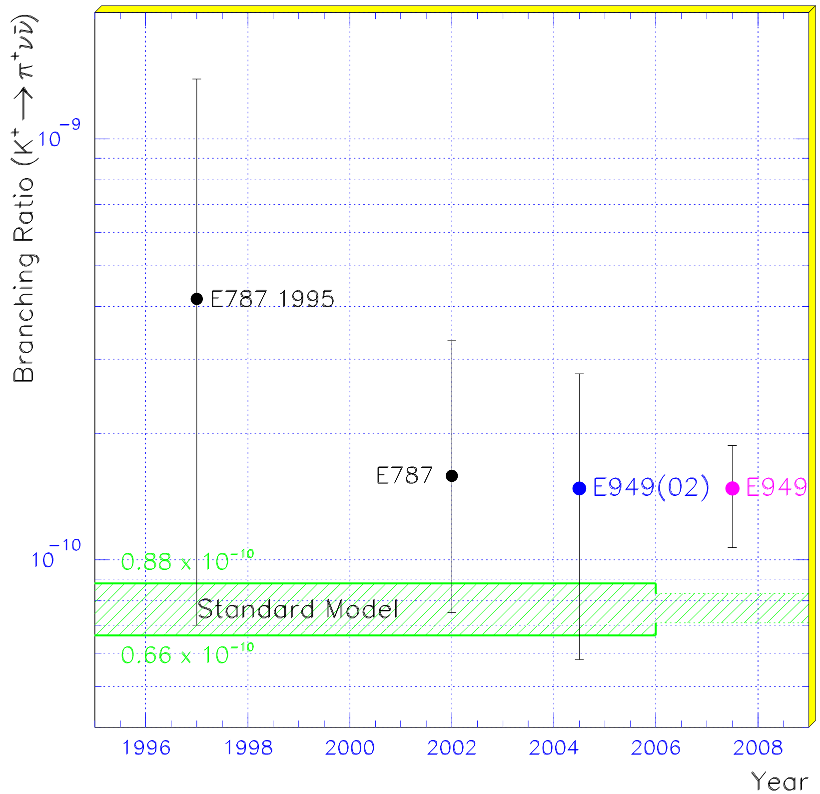
Green lines show $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ impact on Unitarity Triangle: central value (dashed), 68% interval (dot-dash), 90% interval (solid). Theoretical uncertainty is included.

Red ovals show 68%, 90% and 95% areas from other measurements ($|V_{ub}|$, ϵ_K, $\sin 2\beta$, Δm_d, $\Delta m_s/\Delta m_d$)

Provided by Gino Isidori.

Progress in $K^+ \to \pi^+ \nu \bar{\nu}$





E949(02) = combined E787& E949.

E949 projection with full running period.

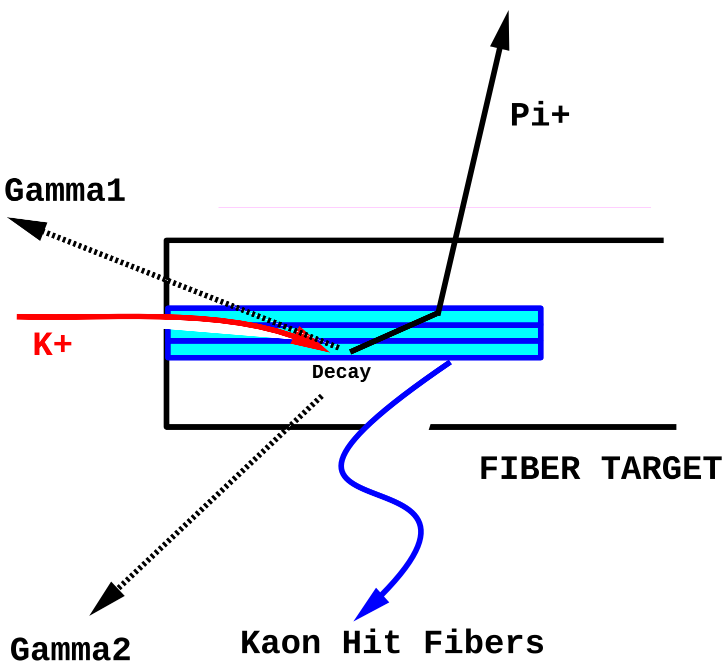
Narrowing of "SM prediction" assumes measurement of B_s mixing consistent with prediction.

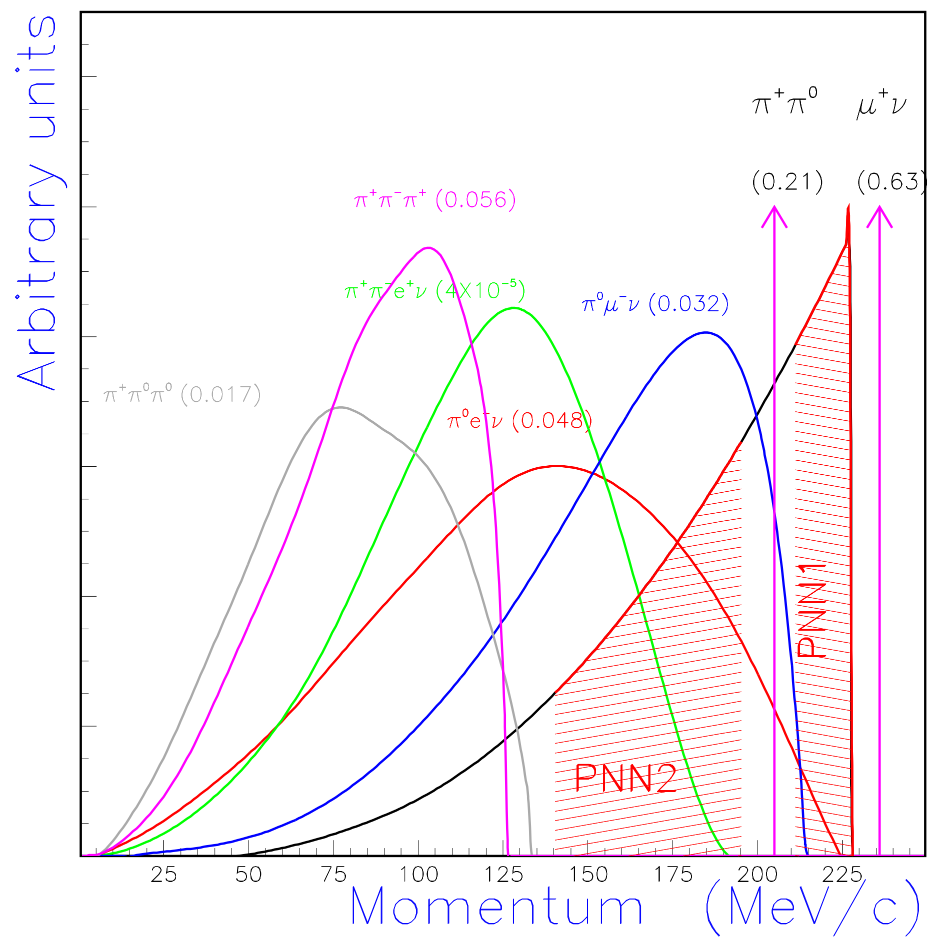
E949 and the future of $K^+ \to \pi^+ \nu\bar{\nu}$

- E949 was approved August 1999 to run for 60 weeks, concurrent with RHIC operation, over three years (U.S. FY2001 - FY2003).
- David Jaffe hired by BNL Physics Dept. (Oct.2000)
- HEP operations at AGS halted for FY2003 (Feb.2002)
- E949 completes successful 12 week run (Jun.2002). AGS functioned well and E949 performed as predicted
- A proposal to continue running E949 has been submitted to the National Science Foundation
- Another stopped-K^+ experiment to measure $K^+ \to \pi^+ \nu\bar{\nu}$ under consideration at KEK in Japan. K^+ decay-in-flight experiments under consideration at FNAL and CERN.
- E949 Analysis of $K^+ \to \pi^+ \nu\bar{\nu}$ for momenta $P(\pi^+) < 195$ MeV/c in progress.

PNN2: $K^+ \to \pi^+\nu\bar{\nu}$ below $K^+ \to \pi^+\pi^0$ peak

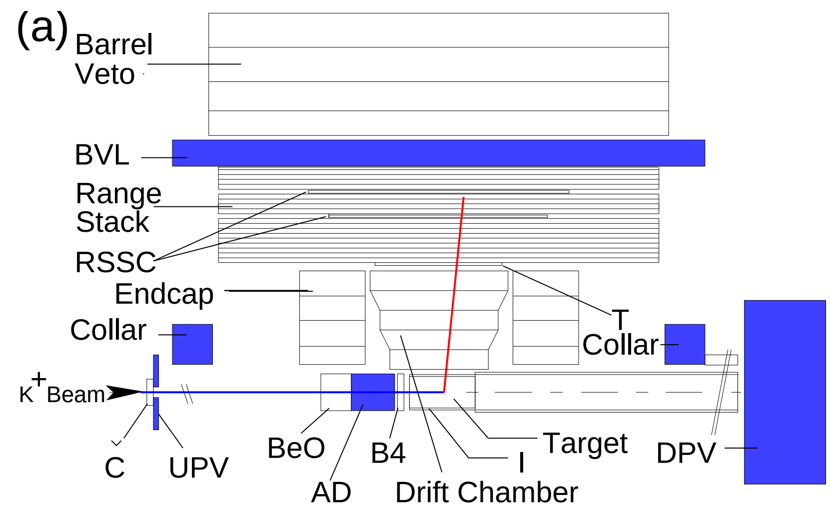
- More phase space than PNN1
- Less loss due to $\pi^+ N$ interactions
- $P(\pi^+) = (140{,}195)$ MeV/c probes more of $K^+ \to \pi^+\nu\bar{\nu}$ spectrum
- Main background mechanism is $K^+ \to \pi^+\pi^0$ followed by π^+ scatter in target.

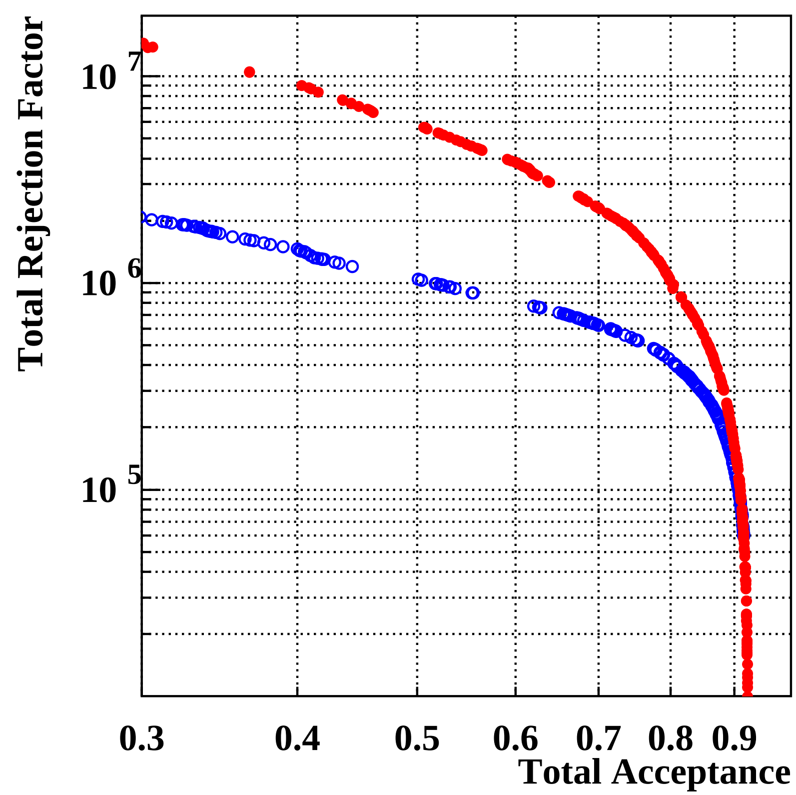




E949 PNN2 analysis

- E787: PNN2 acceptance approx. half PNN1 acceptance
- Goal is equal PNN2 and PNN1 sensitivity with S/B = 1. This implies $\times 2$ increase in acceptance and $\times 5$ increase in background rejection.
- Upgraded photon veto increased PNN1 background rejection. Quantitative assessment of improvement for PNN2 underway.
- Improved algorithms to identify $K^+ \to \pi^+\pi^0$ followed by π^+ scatter in target.





Conclusions

Upgrades of E787 to create E949 were successful.

E949 has observed an additional $K^+ \to \pi^+\nu\bar{\nu}$ candidate and measures $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ for the combined data of E787 and E949.

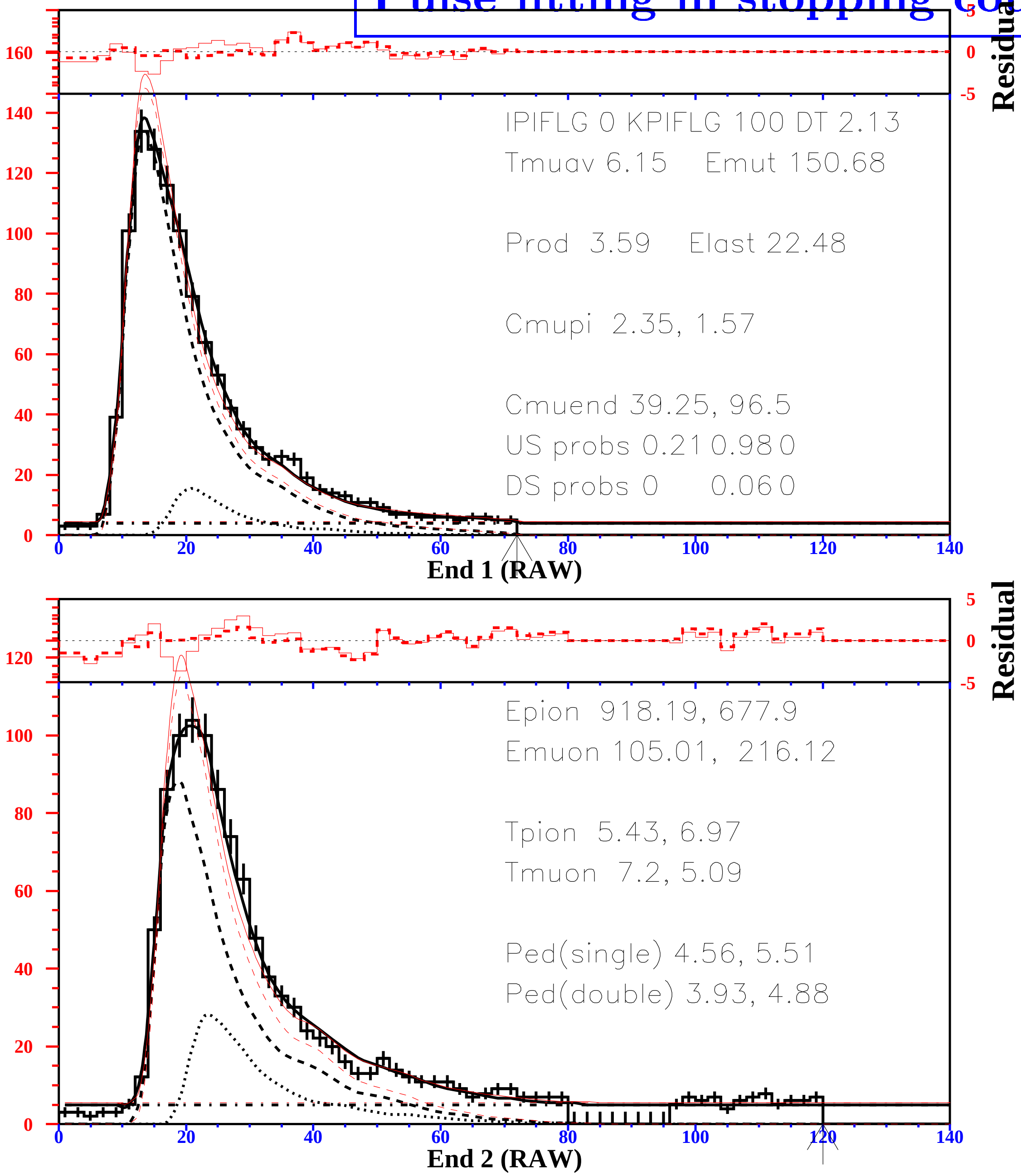
The result is consistent with the current Standard Model prediction.

E949 analysis of $K^+ \to \pi^+\nu\bar{\nu}$ for momenta $P(\pi^+) < 195$ MeV/c in progress.

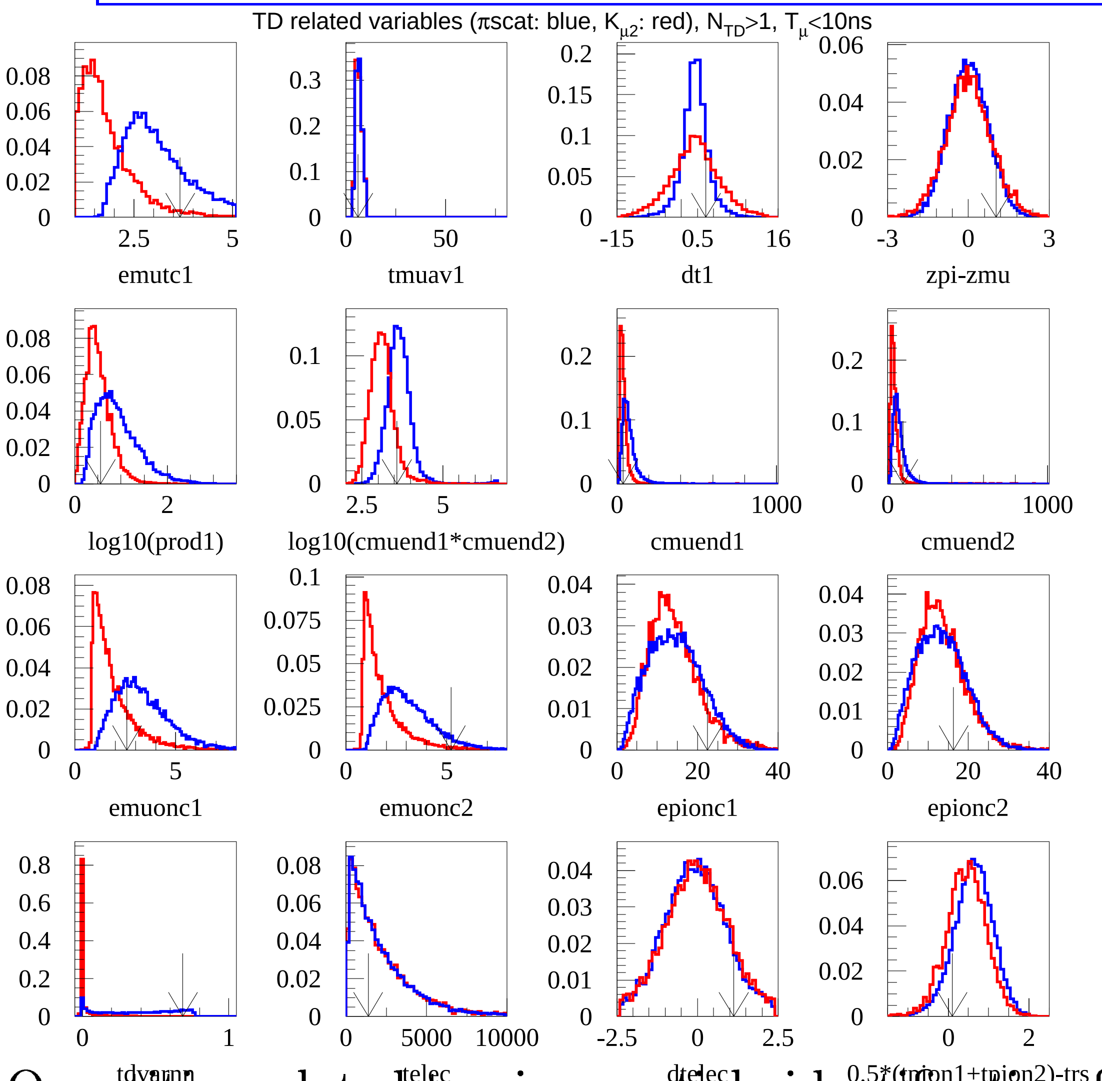
Thanks to my E949 colleagues for their help in preparing this presentation. Thanks also to Gino Isidori for the figure showing the impact of $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ on the Unitarity Triangle.

$\boxed{\textbf{Extras}}$

Pulse fitting in stopping counter

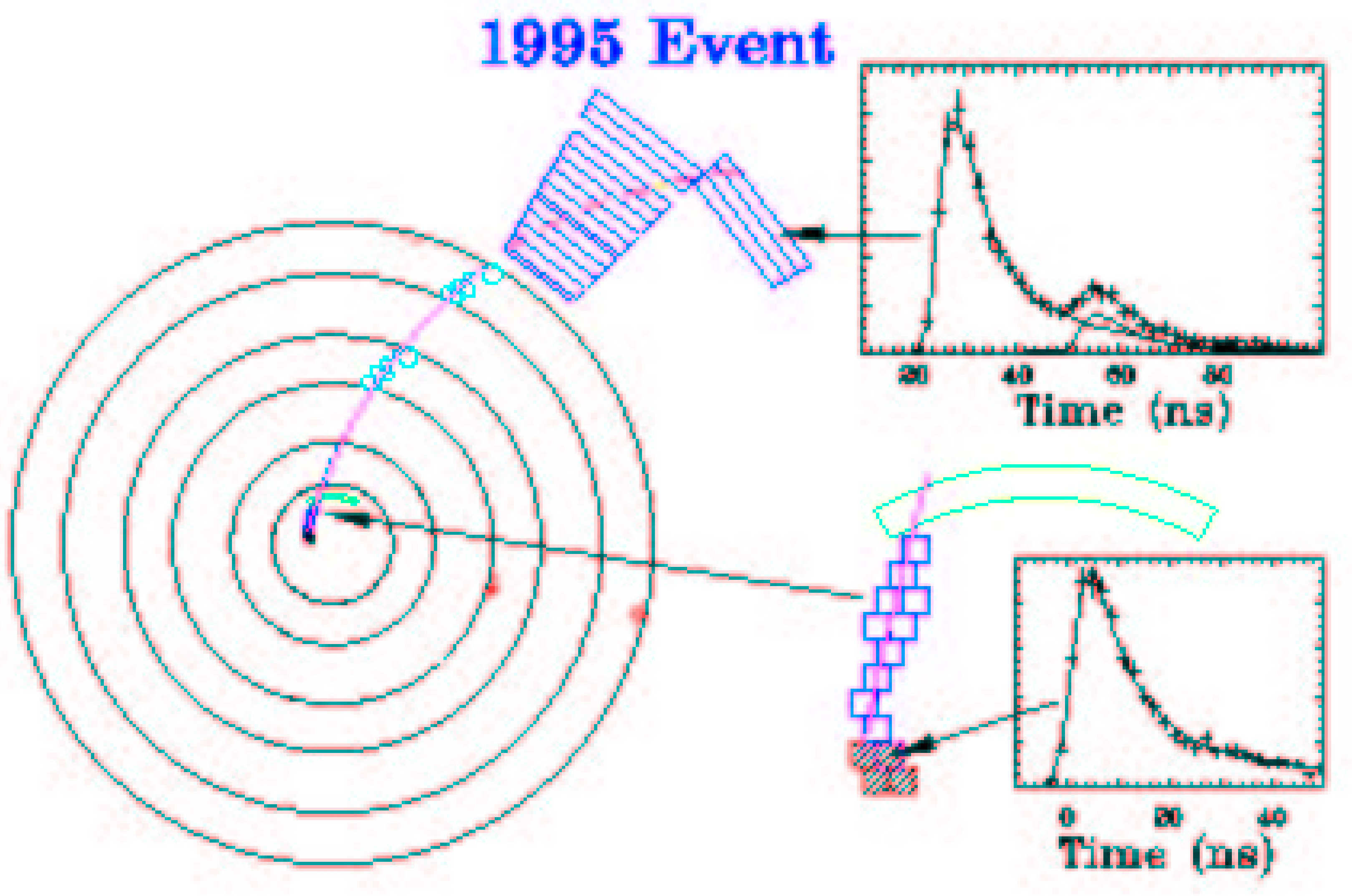


Compare TD properties of candidate with π^+ and μ^+ samples



Quantities related to pion particle identification from TD variables. Events with similar background rejection and fitted muon time < 10 ns are selected. The pion signal (blue) and the muon background (red) are shown in the same plots. The arrows indicate the positions of the candidate event.

Candidate E787A



Candidate E787C